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Plastic Design in A572 (Grade 65) Steel

MECHANICAL PROPERTIES OF ASTM A572 GRADE 65 STEEL

by
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Lehigh University
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A C K N O W L E D G M E N T S

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TABLE OF CONTENTS

		Page
	ABSTRACT	1
1.	INTRODUCTION	2
2.	TESTING PROGRAM AND PROCEDURE	6
3.	TEST RESULTS AND ANALYSIS	23
4.	SUMMARY AND CONCLUSIONS	37
5.	NOMENCLATURE	40
6.	GLOSSARY	42
7.	APPENDIX	45
8.	TABLES AND FIGURES	83
9.	REFERENCES	116

TABLES AND FIGURES

		Page
Table 1	Proposed Program of Work Under Project 343	83
Table 2	Summary of Relevant ASTM Standards	84
Table 3	Program of Tests	85
Table 4	Test Specimens	86
Table 5	Observed Stress	87
Table 6	Observed Strains and Other Mechanical Properties	88
Table 7	Summary of Stresses	89
Table 8	Summary of Strain and Other Mechanical Properties	90
Table 9	Average Values of Groups of Specimens	91
Table 10	Ratio σ_{yd}/σ_{ys}	92
Table 11	Simulated Mill Tests and Mill Data	93
Figure 1	Sketch Defining σ_p, σ_{uy}, $\sigma_{\ell y}$, σ_{yd} and σ_{ys}	94
Figure 2	Sketch Defining E_{st1}, E_{st2} and E_{st3}	95
Figure 3	Sketch Defining $E_{st1(b)}$	96
Figure 4	Typical Graph from Autographic Recorder	97
Figure 5	Typical Complete Stress-Strain Curve for A572 (Grade 65) Steel	98
Figure 6	Idealized Stress-Strain Curve for A572 (Grade 65) Steel (with strain-hardening)	99
Figure 7	Idealized Stress-Strain Curve for A7, A441 and A572 (Grade 65) Steels	100
Figure 8	Typical Complete Stress-Strain Curves for A36, A441 and A572 (Grade 65) Steels	101

		Page
Figure 9	Histograms for σ_{yd}, σ_{ys}, and σ_u	102
Figure 10	Histograms for ϵ_{st}, Percent Elongation and Percent Reduction of Area	103
Figure 11	Histograms for E_{st2}, $E_{st3(a)}$ and $E_{st3(b)}$	104
Figure 12	Histogram for Specimen Thickness	105
Figure 13	Variation of σ_{yd} and σ_{ys} with Thickness	105
Figure 14	Variation of ϵ_{st} and E_{st2} with thickness	105
Figure 15	Histogram for Weight of Shape	106
Figure 16	Variation of σ_{yd} and σ_{ys} with Weight of Shape	106
Figure 17	Variation of ϵ_{st} and E_{st2} with Weight of Shape	106
Figure 18	Shape of the Specimen	107
Figure 19	Scribe and Punch Marks on the Faces of the Specimen	108
Figure 20	Front view of section through crossheads showing the arrangment of grip spreaders and grip retainers.	109
Figure 21	Side view of section through crossheads showing the correct position of the specimen and the grips.	110
Figure 22	A specimen with both extensometers mounted	111
Figure 23	Measurement on the fractured specimen	112

ABSTRACT

This study forms a part of a research project (Fritz Laboratory Project 343) initiated to explore the possibility of extending plastic design concepts to structures of ASTM A572 (Grade 65) Steel. The overall objective was to study the mechanical properties of this material with particular emphasis on the properties in the inelastic range. This report includes discussion of the testing procedure, the testing machine and the instruments used. After a general discussion of the mechanical properties of steel, results of fifty-two tension specimens from plates and shapes of A572 (Grade 65) Steel are summarized.

This report constitutes the most complete study to date of the properties of higher grade of steel. The strain-hardening range of the material is studied closely and more refined techniques for the evaluation of the strain-hardening modulus are developed. Various steps of the testing procedure are studied in some detail. In particular, the phenomenon of reversal of the motor when it is shut off was examined to make sure that it did not cause unloading.

It is found that the A572 (Grade 65) Steel exhibits mechanical properties in the inelastic region that are similar to those of structural carbon steel. The strain-hardening modulus is not so low as to impose unduly severe restrictions for the compactness of shapes. Further study with a view to extending plastic design concepts to structures of this material is, therefore, appropriate.

1. INTRODUCTION

Plastic design concepts and procedures for ASTM A36 steel have gained wide acceptance during the past decade and are now an important part of the AISC Specifications.[1]

Recent advances in metallurgical techniques have led to the development of a number of low-alloy steels with yield strength higher than that of structural carbon steel covered by ASTM A36.[2] These high-strength low alloy steels have found increasing use during the last few years and need was felt of extending plastic design principles to such steels. A project was initiated at Fritz Engineering Laboratory in 1962 to study the plastic behavior of structural members and frames of steels covered by ASTM A242, A440 and A441 with specified yield strength of 42-50 ksi.[3] This research has resulted in design recommendations for such steels.[3,4,5]

The next step was to investigate the low alloy steels with higher strength such as those covered by ASTM A572. The grade with a yield strength of 65 ksi has the highest strength in the range of steels covered by this standard. Hence, a new project entitled "Plastic Design in A572 (Grade 65) Steel" was sponsored in early 1967 by the American Institute of Steel Construction with a view towards extending plastic design techniques to include steels with a yield strength of 65 ksi. A comprehensive program was proposed which included study of mechanical properties, stub columns, beams, etc., details of which are included in Table 1. Since little information relating to A572 steels is available, it was decided to test a number of tension specimens to determine the mechanical properties of the Grade 65 material.

A study of the mechanical properties, especially those in the inelastic region, namely, the strain-hardening strain and the strain-hardening modulus is particularly relevant with regard to the following problems in plastic design.

1) Hinge formation and mechanism theory,
2) Lateral-torsional buckling,
3) Lateral bracing spacing,
4) Local buckling of web and flange,
5) Rotation capacity,
6) Deflection.

Of particular interest in this study is the magnitude of the strain-hardening modulus. Beams and columns of a plastically designed frame as also the plate elements constituting the cross sections of the beams and columns must be capable of undergoing large deformations in the inelastic range so that the basic assumptions of plastic design are satisfied and no premature failure due to local or lateral buckling occurs.[5] The value of the strain-hardening modulus E_{st} and the strain-hardening strain ϵ_{st} play an important part in the development of criteria to prevent such failures. Two examples show the dependence of important functions upon ϵ_{st} and E_{st}: The maximum rotation capacity R_m for a wide-flange shape is given approximately by[5]

$$R_m = 0.8\left\{\frac{\epsilon_{st}}{\epsilon_y} - 1\right\}$$

where ϵ_{st} = Strain at onset of strain-hardening

ϵ_y[2] = Strain at first yield

As a second example, the critical length L_{cr} of lateral bracing spacing is given by[5]

$$L_{cr} = \frac{\pi r_y}{K \quad \epsilon_y \quad 1 + \frac{0.56E}{E_{st}}}$$

where r_y = Weak axis radius of gyration

E = Young's modulus,

E_{st} = Strain-hardening modulus,

K = A coefficient whose value depends on the stress field in L_{cr}.

The object of this report is to provide data on the mechanical properties of A572 (Grade 65) Steel with special emphasis on those more pertinent to plastic design and as a contribution towards the feasibility of extending the concepts of plastic design up to 65 ksi material.

ASTM A572 was issued as a standard for the first time in September 1966.[2] It covers "Standard Specification for High-Strength Low-Alloy Columbium-Vanadium Steels of Structural Quality." Important ASTM Specifications for the chemical composition and the mechanical properties of A572 steel as also of A36, A242, A440 and A441 steels are contained in Table 2.

The higher strength of low alloy structural steels is due to small amounts of alloying elements. The higher strength of A572 steels is attributed to small amounts of nitrogen and vanadium. The addition of columbium promotes a fine grained structure with increased notch toughness. Four types of alternative combinations of these elements are specified as detailed in Table 2.

2. TEST PROGRAM AND TEST PROCEDURES

2.1 TEST PROGRAM

A fairly extensive program of testing tension specimens was instituted using a 120 kip Tinius-Olsen universal testing machine of the screw-power type. Detailed procedures followed are contained in the appendix found at the end of this report.

The program of tests is given in Tables 3 and 4. Two manufacturers supplied a total of forty-two tension specimens. Ten more specimens were fabricated at the Fritz Engineering Laboratory. Four of these came from the undeformed portion of a 12B19 beam previously tested under moment gradient and six from a piece of 10WF54 left over after fabrication of two stub columns.[6,7]

A pilot test was run to determine approximately the properties of the material to facilitate a proper formulation of the testing procedure. The other specimens were tested by groups of students working in parties of two each. The author collaborated on twenty-three of these tests.

2.2 SELECTION OF MATERIAL

Material was received from two manufacturers and is designated as Material A and Material B. All the specimens of Material A came from webs and flanges of 16WF71 and 16WF88. Material B was from plates - 1/4", 3/8" and 1/2" thick and also from the webs and flanges of 12B19, 16B26, 14WF30, 12WF36, 16WF36, 10WF39 and 10WF54. Complete details are given in Tables 3 and 4.

All specimens were fabricated to conform to ASTM A370 using an 8 in. gage.[2] They were tested in the as-received condition except that any loose scale was removed. No attempt was made to remove tight mill scale. None of the original surfaces were milled, only the edges were machined.

2.3 TEST PROCEDURES

The rationale of testing instructions are now briefly reviewed. Also discussed are the difficulties encountered with the machine and the strain-measuring instruments.

1) Testing Machine and Tension Testing

The 120 kip Tinius-Olsen machine which was used in this series of tests is a screw power type with a speed selector which provides a crosshead speed of from 0.025 ipm (inches per minute) up to 10 ipm. According to the manufacturer's data, the crosshead speed indicated on the speed selector is maintained onstant at all loads. However, the strain rate, which is the significant factor which influences the stress level, depends on a number of factors such as crosshead speed, shape of the specimen, elongation within the grips and also on whether the specimen is in elastic or plastic or strain-hardening range. Thus, with presently available equipment, there was no way of testing under a uniform strain rate with this machine. Instead, the strain rate was observed, where possible, by a timer.

Since it was considered desirable to keep the strain rate as low as possible with a view to minimizing its influence on stress levels, a crosshead speed of 0.025 ipm was specified. This is the minimum speed indicated on the speed selector as also the minimum speed at which the machine works smoothly at all loads. It would have been possible to run the machine at a lower speed but such lower speeds were not attempted since the absence of definite markings on the speed selector would have introduced an additional undesirable variable.

There is one source of possible error which was not noted until after most of the tests were completed. The instructions for obtaining the static yield load did not originally emphasize stalling of the machine by gradually reducing the crosshead speed so as to avoid reversal of the motor. This reversal which occurs when the 'STOP' button is pushed or if the speed selector is set to zero could possibly result in unloading of the specimen and thereby give lower values for the static yield stress level. However, later observations on the machine have shown that the lower crosshead continues to move and thus strain the specimen even after the motor reverses on being switched off. Thus, there is no danger of any unloading due to this effect.

2) Instrumentation

Two types of strain-measuring instruments were used as noted in the Appendix. One was an extensometer with a mechanical dial gage which was mounted on one side of the specimen while the autographic extensometer which was connected to the recorder was mounted on the other side. The smallest magnification of 400 was used for the recorder to obtain the entire strain-hardening range in one run of the drum.

Although both the autographic recorder and the dial gage were used to record strains, unfortunately no attempt was made in the early tests to correlate the results. After about thirty specimens were tested, lack of agreement between certain of the two sets of data was noticed. It was not possible to verify any of the previous tests because in most cases, complete dial gage data were not available. Later, complete records of dial gage readings were maintained and results compared with those obtained autographically. Excellent agreement was observed in some cases and startling disagreement in some others. However, there was no discernible pattern from which to draw any definite conclusion. Special tests for checking both instruments again indicated good agreement. It was then decided to rely on the dial gage readings for a number of reasons to be discussed below.

Firstly, a mechanical instrument may be considered inherently more reliable. Secondly, the dial gage always gave more realistic data in the elastic range, that is the value of E was around 30,000 ksi. As against that, the graph sometimes gave a much lower value of E and in all such cases, the disagreement between the dial gage and the graph was more pronounced in the plastic range. Thirdly, while the engagement of the conical points of the dial gage into the punched holes on the specimen was generally considered satisfactory, the same could not be said of the knife-edge of the extensometer. There was no positive device to maintain the position of the knife-edge, and a slip in the grips was often accompanied by slip of the knife-edge. This by itself, was probably not serious because it appeared on the graph and could be accounted for. But if there was a creep of the knife-edge during straining, it was impossible to detect. This possibility seemed particularly strong in the plastic region when the mill scale under the knife-edge became loose.

Marking of scribe lines on the specimen for engaging the knife-edge was tried on one specimen but not considered a success. A number of scribe lines were necessary for the various runs of the autographic recorder and it was difficult to mark these accurately. This made it difficult to bring the drum to zero position. Further, the scribe lines, which were never deep too start with, tended to flatten out in the plastic range and became ineffective.

All these factors coupled with the lack of sensitivity of the autographic recorder as noted earlier cast some doubt on the realibility of the graph.

It is interesting to note that wherever there was pronounced disagreement between the graph and the dial gage, the strains as recorded by the graph were almost invariably higher. In other words, the movement of the knife-edge was greater than the corresponding line on the specimen. This appears rather strange because creep of the knife-edge may be expected to record lower strains.

Values of strain at strain-hardening ϵ_{st} and the strain-hardening modulus E_{st2} based on dial gage readings are marked with an asterisk * in Table 6.

2.4 MECHANICAL PROPERTIES

The following mechanical properties were determined from the tension tests. Figures 1, 2 and 3 are typical and indicate the terms in a graphical way. The glossary defines each term.

1. Proportional limit σ_p
2. Upper yield point σ_{uy}

3. Lower yield point $\sigma_{\ell y}$

4. Dynamic yield stress level σ_{yd}

5. Static yield stress level σ_{ys}

6. Tensile strength (ultimate strength) σ_u

7. Fracture stress σ_f

8. Strain at first yield ϵ_y

9. Young's Modulus E

10. Strain at onset of strain-hardening ϵ_{st}

11. Percent Elongation (in 8 in.)

12. Percent reduction of area

13. Strain-hardening Modulus E_{st}

Of these the properties most important in plastic design are:

1. Static yield σ_{ys}

2. Yield strain ϵ_y

3. Strain at onset of strain-hardening ϵ_{st}

4. Strain-hardening modulus E_{st}

5. Tensile strength (ultimate strength) σ_u

A typical graph from the autographic recorder is shown in Fig. 4 and a typical complete stress-strain curve obtained from one of the tests is shown in Figure 5.

1) Proportional Limit

The proportional limit σ_p is the maximum stress up to which a linear stress-strain relationship is exhibited. However, due to the practical difficulty of determining such a stress, it has been the practice to define σ_p as the stress corresponding to a specified offset from the initial straight line. The CRC guide specified the offset as 10 micro-in./in.[8] Due to the low magnification used in the present series of tests this value was too low for practical use. A higher value of 100 micro in./in. was, therefore, used. See Fig. 1. However there is no practical significance of the value of σ_p. Although structural carbon as well as low alloy steels are expected to exhibit linear elasticity almost up to yielding many tests give lower and widely varying values of σ_p. This can be attributed to two factors: (i) Inaccurate alignment of the specimen and the consequent higher localized stresses due to eccentric load and (ii) Prior plastic deformation in the opposite direction due to cold-straightening, creating the Bauschinger effect.[9]

2) Upper Yield Point

Yield point is defined as the first stress in the material, less than the maximum at which an increase in strain occurs without an increase in stress.[10] When such increase in strain is accompanied by a decrease in stress, the material is said to have exhibited an upper yield point. Referring to Fig. 1, the upper yield point σ_{uy} corresponds to the highest load attained before the plastic range. It is influenced by the strain rate, the grain size and the previous strain-history of the material. In terms of dislocation mechanics, the presence of an upper yield point is attributed to interstital impurities in dislocations which lead to a drop in flow stress after plastic flow has been initiated at the upper yield point.[9] This load is recorded by the maximum pointer on the load dial, as well as by the autographic recorder. However, in many instances in these tests, when the drop in load after the attainment of the highest load was small, the autographic recorder failed to register the load corresponding to σ_{uy}. This is because there is a certain play between the gears operating the rod recording the load and also between the rod and the recording pen so that the recording mechanism is rendered insensitive to small reversals of load. However, σ_{uy} is not an important property and many tension specimens fail to exhibit any upper yield point possibly because of misalignment or the Bauschinger effect.[9]

3) Lower Yield Point

Lower yield point $\sigma_{\ell y}$ corresponds to the lowest load recorded after the upper yield point has been passed and after the load has reached a temporary dynamic equilibrium condition compensating for the sudden prior slip. This can be recorded from the load dial, keeping a close watch when the load begins to drop. The difference between the load corresponding to $\sigma_{\ell y}$ and the stabilized dynamic yield load is often so small that the recording mechanism fails to record it because of its insensitivity to load reversals.

$\sigma_{\ell y}$ is not a significant quantity and is dependent on the presence of an observed upper yield point and the response of the specimen and the machine after the first slip. Because of these reasons, values of $\sigma_{\ell y}$ are not reported.

4) Dynamic Yield Stress Level

The yield stress level is defined as the average stress during actual yielding in the plastic range.[11] For structural steel, the stress level remains fairly constant from the yield point up to the onset of strain-hardening, provided the strain rate is held constant.

The yield stress level corresponding to the crosshead speed 0.025 ipm is termed the dynamic yield stress level σ_{yd}. The load corresponding to the value of σ_{yd} was recorded using the maximum pointer of the load dial just before stalling the machine at a strain of about 0.005 in./in. which was equivalent to 2 in. on the strain axis of the recorder sheet.[2] It was not possible to stall the machine exactly at a strain of 0.005 in./in. because such accurate control of machine speed was not possible and there was some delayed strain even after stalling of the machine and as explained in the next section.

The value of σ_{yd} at the crosshead speed of 0.5 ipm which is the maximum permitted by ASTM for an 8 in. gage is reported as the yield stress by the mills and is designated σ_{ym}.[2]

5) Static Yield Stress Level

The static yield stress level σ_{ys} may be defined as the value of the yield stress level at zero strain rate. σ_{ys} is an important property of steel and has a significant role to play in plastic design. It is the value which must be used for yield stress in plastic analysis under static loads.

Obtaining a value for σ_{ys} is not merely a matter of stalling the machine and observing the reduced load. The drop in load is due not only to the stalling of the machine. There is the loss due to relaxation.[9] Relaxation is defined as the loss of stress under constant strain. Relaxation loss is time-dependent and the rate of loss drops sharply with time but the full relaxation loss may be realized only after a very long time.

The situation in the test is still more complicated. Many elements of the machine (the columns, screws, crossheads) are subjected to stresses and every drop in load reduces strains in these elements and also in the length of the specimen outside the gage points. Hence, the strain between the gage points continues to increase for a minute or two even after the crosshead has become stationary and the process of relexation is delayed. This is the reason why the load corresponding to σ_{ys} was recorded after an interval of five minutes after stalling the machine at a strain of about 0.005 in./in.[2] This interval was considered a practical minimum for reaching a reasonably stable load.[12] Full relaxation losses were thus not registered but obtaining even a significant part of it would have required waiting for at least a few hours.

Since the yield stress quoted by manufacturers is based on mill tests which are conducted at much higher crosshead speeds, the study of the ratio σ_{yd}/σ_{ys} assumes importance. Such studies have been made for A36, A441 and A514 steels but the A572 steels have not been examined so far.[12] The ratio σ_{yd}/σ_{ys} is studied for the uniform crosshead speed of 0.025 in./min. Four simulated mill tests were carried out and their results reported later together with the data provided by the producers.

ASTM A370 specifies a maximum crosshead speed of 0.5 ipm for 8 in. gage.[2] The speed adopted for this series of tests was only one-twentieth of the maximum stipulated by ASTM and usually used for mill tests. Also the yield load as defined by the ASTM A370 is the load corresponding to a 0.2% effect or 0.5% strain.[2] The latter criterion was used for this series of tests.

6) Tensile Strength

The tensile strength σ_u corresponds to the maximum load on the specimen. This is recorded from the maximum pointer after the load begins to drop off.

7) Fracture Stress

The fracture stress σ_f corresponds to the load at the instant of fracture. The drop in load was rather sharp just before fracture so that it was difficult to record the fracture load. Hence, the value of σ_f should be regarded as approximate only.

8) Strain at First Yield

The strain at first yield ϵ_y was recorded from the dial gage at the instant the load pointer dropped on reaching the upper yield point. However, in the absence of an upper yield point, no observation could be taken. In such cases, even the autographic recorder failed to register a clear value of ϵ_y. Because if this, the observed value of ϵ_y are not included in this report. Instead ϵ_y is computed as σ_{ys}/E.

9) Young's Modulus

Young's modulus E was computed from observations taken as per the procedure detailed in the Appendix. However, the measuring techniques were fined enough to give accurate values of E and therefore, the observed values are not reported here. Its value is assumed at 29,600 ksi.[13]

10) Strain at Onset of Strain-Hardening

Strain at onset of strain-hardening ϵ_{st} was measured from the autographic recorder and later when certain discrepancies appeared as noted earlier, dial gage readings were also taken. The values of ϵ_{st} based on dial gage readings are marked with an asterisk * in Table 6. The process of straining between first yield and the onset of strain-hardening is a discontinuous process due to the formation of successive slip bands. In terms of the modern theory of dislocation mechanics, the value of ϵ_{st} depends on the distribution of dislocations.[9] Previous strain history would also modify the value of ϵ_{st}.

A small reduction in the gage length occured as the knife-edge of the extensometer was lifted off the specimen usually after a strain of 0.0125 which was done to obtain the entire strain-hardening range in one run. In computing ϵ_{st}, no correction was applied to the strain on the second run. In any case, such correction would be small.

11) Percent Elongation and Percent Reduction of Area

Both percent elongation and percent reduction of area at fracture have been used extensively as a measure of ductility although both these quantities depend upon a variety of factors other than the material properties.[9] The "uniform strain" which is the strain corresponding to the point at which the maximum load is recorded in a tension test, is the measure of ductility specified by some standards and is a more consistent material property.[9] Percent elongation represents the sum of uniform strain and a large localized necking strain averaged over the gage length. That is why the gage length is always specified along with percent elongation. However the necking strain itself depends on the cross section. Mechanics of necking in a circular cross section is far different from that in a rectangular cross section. Different width-thickness ratios in specimens of rectangular cross section also exhibit different necking characteristics. This adds further uncertainty to the value of percent elongation. The same applies to percent reduction of area as a measure of ductility.

12) Strain-Hardening Modulus

The strain-hardening modulus E_{st} has received considerable attention in research because of its importance in stability analysis. As already noted in the introduction, E_{st} figures in the lateral buckling criterion under uniform moment and the local buckling criteria of plate elements constituting the cross section of members. In short, the value of E_{st} is very important in the study of inelastic buckling behavior of any member, where any portion of the cross section is subjected to compressive yield stress over a finite length. Many approaches have been used in evaluating E_{st} and some of these are briefly reviewed below. Refer to Figure 2.

E_{st1} is the instantaneous value as measured by a tangent to the curve at the point where strain-hardening commences. In the present series of tests, this value was obtained from the autographic recorder graph. It would be somewhat more difficult to obtain from dial gage readings because a large number of points would need to be taken at close intervals.

E_{st1} is only of academic interest and has little practical significance. The instantaneous value of E_{st} falls off rapidly as strain-hardening progresses and it would be rather unrealistic to use the value of E_{st1} in any stability computations. Besides, the tangent is difficult to determine uniquely and the small drop in load which often precedes the initiation of strain-hardening results in rather high values of E_{st1}. Further, the value of the strain-hardening modulus depends on the distribution of dislocations.[9] All these factors contribute to a wide scatter of values.

In order to approximate the initial instantaneous value, Haaijer defined the stress-strain relationship in the strain-hardening region using three parameters introduced by Ramberg and Osgood.[14,15]

$$\epsilon - \epsilon_{st} = \frac{\sigma - \sigma_y}{E_{st}} + K \left(\frac{\sigma - \sigma_y}{E_{st}} \right)^m$$

where σ and ϵ are respectively the stress and strain, σ_y is the yield stress and K and m are coefficients. The value of E_{st} used in the above equation is designated $E_{st1(a)}$. Values of K, m, and $E_{st1(a)}$ are determined from experimental curves by a curve-fitting technique.

This approach eliminates the uncertainties involved in the graphical construction of the tangent and provides a powerful mathematical tool for the study of incremental stress-strain relationship. $E_{st1(a)}$ was not computed in this series of tests.

Adams and Lay obtained a static strain-hardening modulus designated $E_{st1(b)}$ by using the static load at ϵ_{st} and at a strain equal to $\epsilon_{st} + 0.002$.[4] See Fig. 3. No attempt was made to obtain $E_{st1(b)}$ in this series of tests, because the method appears to introduce uncertainties that raise a question as to the reproducibility of results. The value of ϵ_{st} must be determined in advance and since this value can vary between rather wide limits, the method is sensitive to the variation between the correct value of ϵ_{st} and the strain at which the machine is stopped for observing the static load. Besides, the value of E_{st} is not constant in the increment of 0.002 beyond ϵ_{st}. A further uncertainty is introduced by the possibility of different relaxation losses at the two points.

E_{st2}, which was measured in these present tests and is later reported, is defined as the strain-hardening modulus measured as the chord slope between the strains $\epsilon_{st} + 0.003$ and $\epsilon_{st} + 0.010$. See Fig. 2. This particular range was chosen from the results of the pilot test with a view to confining measurements to a fairly linear and stable range of the curve and eliminating the initial erratic portion of the strain-hardening range of the stress-strain curve. E_{st2} should provide a more conservative value than the other methods because measurements are made at a greater value of strain.

E_{st2} was computed from the autographic recorder in most of the tests. However, when the earlier-mentioned discrepancies between the dial gage readings and the recorder were discovered and the results of the recorder appeared to be in some doubt, it was decided to take more complete dial gage observations on the later tests. Wherever values of E_{st2} are based on dial gage readings, they are marked by an asterisk * in Table 6.

E_{st3} is obtained using the CRC approach.[8] It is the average value in an increment of 0.005 in./in. strain after the onset of strain-hardening. See Fig. 2. For this purpose the onset of strain-hardening is defined as the strain corresponding to the intersection on the stress strain curve of the yield stress level in the plastic range with the tangent to the curve in the strain-hardening range. This tangent is drawn as the average value in an increment of 0.002 in./in. after the apparent onset of strain-hardening. The definition of the onset of strain-hardening is so modified here that the effect of the frequently encountered drop in load immediately prior to the apparent onset of strain-hardening is eliminated.

E_{st3} includes the effect of the steeper initial slope. It should result in E_{st3} being a less conservative value than E_{st2}. The range of strain-hardening is also rather arbitrary and this is quite significant because the influence of strain range on E_{st3} is much greater than on E_{st2}.

In the present series of tests, E_{st3} was measured in two ways. The value measured from the autographic recorder was designated $E_{st3(a)}$ and that measured from dial gage readings designated $E_{st3(b)}$.

No single value of E_{st} can be satisfactorily used in all situations. For incremental analysis, Ramberg and Osgood's equation with $E_{st1(a)}$ would be appropriate. For the simpler buckling analysis, two cases arise; (1) In the first case, the material is assumed to be strained up to ϵ_{st} as in the local buckling analysis and analysis of beams under uniform moment, (2) Here, the material is assumed to be strained well into the strain-hardening range. A suggested value is a stress of $\sigma_y + 1/4\ (\sigma_u - \sigma_y)$.[16] E_{st3} can be used for the first case, but for the second case E_{st2} would be more appropriate. Further, when cold-straightening strains the material well into the strain-hardening range, it may be more appropriate to use E_{st2}.

It may be emphasized again that E_{st} is not a stable material property but depends on factors like distribution of dislocations and previous strain history.[10] Under these circumstances, values of both E_{st2} and E_{st3} (average of $E_{st3(a)}$ and $E_{st3(b)}$) are reported.

3. TEST RESULTS AND ANALYSIS

Results of tests are presented in this section together with pertinent discussion. The data was analyzed using the CDC6400 computer at Lehigh University. Details of the computer program will be made available in a subsequent report.[17]

Table 3 lists the program of tests and Table 4 gives the details of the test specimens. Computed values of the mechanical properties are listed in detail in Tables 5 and 6 and are summarized in Tables 7 and 8. Table 9 contains the average values of some important properties of groups of specimens selected according to (i) origin, (ii) presence or absence of yield lines, (iii) thickness and (iv) weight of shape. Data for the ratio σ_{yd}/σ_{ys} are in Table 10 and the results of the simulated mill tests and the mill data are in Table 11.

A typical graph from the autographic recorder is shown in Fig. 4 and a typical complete stress-strain curve obtained from the tests is shown in Fig. 5. The dips in the curve indicate the points at which the machine was stopped in order to adjust the recording paper. Figure 6 shows an idealized stress-strain curve for A572 (Grade 65) steel up to and including strain-hardening and indicating the average values of the significant properties. The same curve is reproduced in Fig. 7 alongside similar curves of A7 and A441 steels. Figure 8 shows typical complete stress-strain curves for A36, A441 and A572 (Grade 65) Steels.

A summary of the average values of the mechanical properties listed in Chapter 2 is given below:

1. $\sigma_p = 57.0$ ksi
2. $\sigma_{uy} = 66.7$ ksi
3. $\sigma_{\ell y}$ is not reported for reasons stated in Chapter 2.
4. $\sigma_{yd} = 64.6$ ksi
5. $\sigma_{ys} = 62.1$ ksi
6. $\sigma_u = 85.7$ ksi
7. $\sigma_f = 67.9$ ksi
8. $\epsilon_y = 0.00211$ in/in. $= \sigma_{ys}/E$
9. E is assumed as 29,600 ksi
10. $\epsilon_{st} = 0.0186$ in./in.
11. Percent Elongation (in 8 in.) = 21.5

    Percent Reduction of Area = 51.0
12. $E_{st1} = 2{,}979$ ksi

    $E_{st2} = 553$ ksi

    $E_{st3(a)} = 771$ ksi

    $E_{st3(b)} = 704$ ksi

    E_{st3} = Average of $E_{st3(a)}$ and $E_{st3(b)}$ = 737 ksi
13. $\sigma_{yd}/\sigma_{ys} = 1.040$ for a crosshead speed of 0.025 ipm.
14. $\sigma_{ym} = 69.3$ ksi

These results are consistent with the relevant ASTM A572 requirements. Some of these will now be discussed.

Some of the important results from Tables 5 and 7 are reproduced below. All values are in ksi.

Property	Minimum	Maximum	Average	Standard Deviation
σ_p	30.8	72.0	57.0	9.9
σ_{uy}	59.8	72.0	66.7	2.6
σ_{yd}	58.4	69.9	64.6	2.6
σ_{ys}	57.0	66.3	62.1	2.3
σ_u	80.4	89.6	85.7	2.2
σ_f	61.1	79.3	67.9	3.4

1) Proportional Limit

As already discussed in Chapter 2, the proportional limit is influenced by many factors. This is reflected in the test results summarized above.

The observed average value of σ_p corresponds to 85.4% of the upper yield point, which is about what one would expect.

2) Upper Yield Point

Only forty-two specimens registered upper yield. Figure 9 shows the histogram for the values of σ_{uy}. Only three specimens exhibited values of σ_{uy} lower by 0.2 ksi than the dynamic yield stress level. Otherwise, the values of σ_{uy} were higher than those of σ_{yd}, the average difference being 3.1 ksi or 4.65% of the average value of σ_{uy}. This increase is registered in spite of the fact that the strain rate near upper yield point is smaller than in the plastic range.[12] The higher value of σ_{uy} can be attributed to the higher stress required to initiate plastic flow compared to the stress required for sustaining it.

3) Lower Yield Point

Values of the lower yield point are not reported for reasons already discussed in Chapter 2.

4) Dyanmic Yield Stress Level

Figure 9 shows the histogram for the values of σ_{yd}. The scatter is much less than for lower grades of steel.[18]

5) Static Yield Stress Level

The values for σ_{ys} also exhibit a smaller scatter than for lower grades of steel as shown by the histogram in Fig. 9.[18]

The effect of strain rate on the relationsip of σ_{yd} and σ_{ys} and the influence of factors like thickness of specimen on the value of σ_{ys} are discussed later.

6) Tensile Strength

Among the values of stresses, the values of the tensile strength show the minimum scatter as indicated by the histogram in Fig. 9.

Like the values of σ_{yd} and σ_{ys}, the values of σ_u show smaller scatter than for lower grades of steel.[18] However, the results of the three flange specimens of Material A with tensile strength higher than the stress corresponding to 120 kips, the capacity of the machine, are not included. The values of σ_u for these specimens were larger than 92 ksi and inclusion of these values would have resulted in a slightly higher value of σ_u.

7) Fracture Stress

The difficulties of observing the fracture load have been discussed in Chapter 2. Further uncertainty is introduced by the practice of evaluating fracture stress using the original area of the specimen and the differences in the mechanics of necking of different shapes of cross section.[9] The test values of σ_f appear to reflect these problems.

8) Strain at First Yield

The value of the strain at first yield as reported here is 0.00211 in./in. which is equal to the quotient of the average value of σ_{ys} and Young's modulus. This has been discussed in Chapter 2.

9) Young's Modulus

As already discussed in Chapter 2, the values of E as computed from the tests are not reported since the techniques used were not refined enough. Instead, the value is adopted from a series of careful tests reported in Ref. 13.

Some of the important results from Tables 6 and 7 are now reproduced below:

Property	Minimum	Maximum	Average	Standard Deviation
ϵ_y, in./in.	0.0095	0.0328	0.0186	0.0052
Elongation, %	18.0	36.1	21.5	2.7
Reduction of Area, %	36.4	62.3	51.0	6.8
E_{st1}, ksi	393	9825	2979	2400
E_{st2}, ksi	322	775	553	95
$E_{st3(a)}$, ksi	382	1160	771	186
$E_{st3(b)}$, ksi	220	1122	704	197

10) Strain at Onset of Strain-Hardening

Figure 9 shows the histogram for the values of ϵ_y. The test results for the values of ϵ_y are summarized on the preceding page.

The coefficient of variation is 27.9%. As noted in Chapter 2, the modern science of materials asserts that the stress-strain relationship in the inelastic range is determined by the random nature of the distribution of dislocations and the prior strain history.[10] This would suggest that ϵ_{st} may not be a characteristic mechanical property and would explain the wide scatter in the values of ϵ_{st}.

11) Percent Elongation and Percent Reduction of Area

The limitations of the values of the percent elongation and the percent reduction of area as a measure of ductility have been discussed in Chapter 2. The histograms for both values are in Fig. 9 and a brief summary of the test values is given earlier.

Except for one specimen with a value of 36.1, the maximum value of the percent elongation was 24.9. The values for percent reduction of area exhibit a much bigger scatter. Also, a study of Figure 9 indicates that there is no central tendency for percent elongation of area in contrast with the distribution of percent elongation.

12) Strain-Hardening Modulus

Various approaches to the measurement of E_{st}, the value of which is of particular interest, have been discussed in Chapter 2. Important results have been summarized at the end of section 9 earlier. Histograms for E_{st2}, $E_{st3(a)}$ and $E_{st3(b)}$ are shown in Fig. 11.

E_{st1} varies from 393 to 9825. This wide scatter of values is in keeping with the known erratic nature of the straining process in the region of the onset of strain-hardening and is also in keeping with inherent difficulties in determining this function.

By eliminating the initial erratic portion of the strain-hardening range of the stress-strain curve and confining measurements to a relatively linear portion of the curve, the resulting value of E_{st2} exhibits a smaller scatter and a much smaller standard deviation than E_{st3}. Further, since the slope of stress-strain curve reduces with increasing strain, the average value of E_{st2} is lower.

The average value of E_{st2} at 553 ksi for A572 (Grade 65) steel compares favorably with the value of 572 ksi for A7 steel, since the later value lies somewhere between E_{st2} and E_{st3}. See Fig. 7. This would indicate that the limits on the width-thickness ratios of shapes and the bracing spacing requirements would not be too restrictive. This is fortunate, since the A572 (Grade 65) steel is limited to shapes of Group 1 with high width-thickness ratios so that a low value of E_{st2} would render most of them non-compact.

According to Ref. 9, the effective value of E_{st} in compression is somewhat larger than in tension for a material otherwise exhibiting the same stress-strain relationship in compression and tension. This is because of the Poisson effect, which causes a change in cross section as a result of the lateral strain which accompanies longitudinal strain. The effect is more pronounced in the inelastic range due to a higher value of Poisson's ratio.

This higher value of E_{st} has been noted in previous tests. The following table of values of E_{st} are reproduced from unpublished data on twenty-one tension tests and twenty compression tests on A7 steel conducted at the Fritz Engineering Laboratory. Values of E_{st} are read as chords in the linear portion of the curve and lie somewhere between E_{st3} and E_{st2}. All values are in ksi

	Minimum	Maximum	Average
21 Tension Tests	465	750	572
20 Compression Tests	520	855	695

A series of ten compression tests on specimens fabricated out of the same material from which tension specimens were prepared, has been recently completed.[19] A preliminary analysis has given an average value of E_{st2} as 820 ksi.

However, the Poisson effect cannot fully account for the substantially higher test values of E_{st} in compression. And this gives rise to the question as to whether or not E_{st} should be determined from tension tests or from compression tests when the resulting values are to be used in calculations involving buckling problems.

13) Effect of Strain-Rate

Rao et al have pointed out that in the plastic range, the elongation of the length of the specimen undergoing plastic deformation accounts for all the movement of the crosshead.[12] Assuming such length to be about 10", a crosshead speed of 0.025 ipm would give a strain rate of about 42 micro in./in./sec.

On seventeen tests, the strain-rate $\dot{\epsilon}$ was observed using a timer The values of $\dot{\epsilon}$ varied from 21 to 83 micro in./in./sec. giving an average value of 44. Such large variation was probably caused by the extreme sensitivity of crosshead speed to the position of the speed selector pointer. Thus, the values cannot be confidently specified as the strain-rate for the corresponding value of σ_{yd} since the dynamic yield load was observed during the first run of the autographic recorder and the strain-rate was observed during the second run and the speed selector was manipulated in the meanwhile. However, the expotential relationship derived in Ref. 12 would suggest that the effect of such variation in the value of $\dot{\epsilon}$ on the value of the ratio σ_{yd}/σ_{ys} should be small so that a valid comparison with the results of Ref. 12 could still be made.

Test values of σ_{yd}/σ_{ys} are given in Table 10. Projecting the results derived in Ref. 12 for A36 and A441 steels, the following comparison is obtained. It indicates excellent agreement.

	$\dot{\epsilon}$ = 44 micro in./in./sec. Projected	Observed values for A572(Grade 65)
σ_{yd}/σ_{ys}	1.040	1.040
$\sigma_{yd}-\sigma_{ys}$	2.88	2.50

14) Simulated Mill Tests

Simulated mill tests were conducted on four specimens, two from material A and two from material B. A crosshead speed of 0.5 ipm which is the maximum permitted by ASTM for 8 in. gage was used.[2] Table 10 lists the results together with the mill test data furnished by the producers.

Mill tests are invariably performed on webs. Unfortunately, only one web specimen - from 12B19 of material B was available for conducting simulated mill tests. No plate specimens were available Because of this, comparing the data is difficult. The only direct comparison is afforded by the web of 12B19.

	σ_{ym}, ksi	σ_u, ksi	Percent Elongation
Simulated Mill Test	71.8	89.2	18.6
Mill Data	71.8	94.8	17.0

Although it is in part a happenstance, the agreement at yield is exact. Even for the entire lot of material, the agreement was within 2%.

All the test results of Table 10 meet with the tensile requirements of ASTM. See Table 2.

An interesting comparison with the following equation derived in Ref. 12 can be made

$$\sigma_{yd} - \sigma_{ys} = 3.2 + 0.001\ \dot{\epsilon}$$

Assuming that in the plastic range, elongation between the gage points accounts for the full crosshead speed, the maximum possible value of $\dot{\epsilon}$ works out to be 1,040 micro in./in./sec. for a crosshead speed of 0.5 ipm. The corresponding value of $\sigma_{yd} - \sigma_{ys} = 4.2$ ksi. Test results are listed on the following page.

Material	Specimen from	σ_{ys}, ksi average, No. of specimens in brackets	σ_{ym}, ksi from simulated mill tests	σ_{ym}, ksi from mill data	$\sigma_{ym} - \sigma_{ys}$ ksi
A	Web-16W88	61.0(2)	---	71.1	10.1
"	Flange-16W71	62.9(2)	67.9	---	5.0
"	Web-16W71	61.8(2)	---	73.0	12.2
B	1/2"plate	61.4(3)	---	66.9	5.5
"	3/8"plate	61.1(4)	---	65.0	3.9
"	1/4"plate	63.9(4)	---	71.8	7.9
"	Flange-12B19	65.1(4)	69.6	---	4.5
"	Web-12B19	64.9(4)	71.8	71.8	6.9
"	Web-16B26	60.2(2)	---	70.5	10.3
"	Web-10W39	59.7(2)	---	71.5	11.8
"	Web-10W54	57.8(2)	---	72.9	15.1
"	Average of simulated mill tests		70.7		5.8
A&B	Average of mill data			70.5	9.3

All except one of the values of $\sigma_{ym} - \sigma_{ys}$ are larger than 4.2 ksi, the average being 9.3 ksi. The average for the simulated mill tests is 5.8 ksi. The high value of $\sigma_{ym} - \sigma_{ys}$ for the mill data could be attributed to the fact that the mills often tend to report the upper yield point for the value of σ_{ym}.[11]

15) Effect of Material Source

Values of σ_{ys} and σ_u for material A were slightly higher than for material B although all the Material A specimens came from thicker material.

	Material A	Material B
σ_{ys}, ksi	62.4	62.0
σ_u, ksi	87.5	85.5

In fact both 16W71 and 16W88 from which all of the material A specimens were fabricated, are outside of group 1 shapes to which A572 (Grade 65) steel is restricted. Hence, it appears that the material B supplied for testing was probably on the low side of mill distribution.

16) Effect of Origin and Location of Specimen

Table 9 lists some properties of plate, web and flange specimens The following may be particularly noted

	Plate	Web	Flange
σ_{ys}, ksi	62.2	61.9	62.2
σ_u, ksi	86.3	85.3	85.8
E_{st2}, ksi	525	530	569

Generally, the effect of rolling to a smaller thickness and the consequent faster cooling are thought to produce a stronger web although the distances are small. The reverse was obtained in these tests. The somewhat higher strength of the flange in the list above is partly due to the high flange strength of material A. As shown in Table 7 web strength was slightly higher than flange strength for material B but every flange specimen of material A was stronger than its corresponding web specimen.

17) Effect of Yield Lines

Table 9 compares some properties of specimens with yield lines with specimens of some material, heat, origin and shape but without yield lines. No significant influence of yield lines can be noted. From the work of

Ref. 3 it was expected that E_{st} would be substantially lower. If any thing, it was higher for the five rotarized specimen in the current test program. The conclusion here is important, because it means that rotarizing will not reduce the local buckling strength in the inelastic region, at least if these five specimens can be assumed to be a sufficiently large sample.

18) Effect of Thickness

Some properties of specimens divided into groups according to thickness are given in Table 9. Graphical presentation of variation with thickness is shown in Fig. 13 for σ_{yd} and σ_{ys} and in Fig. 14 for ϵ_{st} and E_{st2}. Although the values of σ_{yd}, σ_{ys} and σ_u are high for thickness 0.801-0.900 in., it may be concluded that strength reduces with increased thickness, because the stronger thick specimens belong to material A and none of these have been tested in smaller thickness. The value of ϵ_{st} increases with increased thickness.

An interesting side to the study of the influence of thickness is the values of the percent reduction of area. As the table below shows the thicker specimens exhibit a higher value for the value of the percent reduction of area. This is probably due to the influence of the width-thickness ratio of the cross section of the specimen on the mechanics of necking.

Thickness, in.	Percent Reduction of Area
0.201-0.300	45.3
0.301-0.400	51.8
0.401-0.500	50.3
0.501-0.600	55.6
0.601-0.700	53.7
0.701-0.800	No data
0.801-0.900	56.0

19) Effect of Weight of Shape

Table 9 lists some properties of specimens divided according to weight of shape. Figure 16 shows σ_{yd} and σ_{ys} and Fig. 17 shows ϵ_{st} and E_{st2} as functions of weight of shape. Here too, the uneven distribution of specimens persists. All the higher strength material A specimens belong to heavier shapes. However, the same general conclusions can be drawn as in the previous case. With increased thickness, σ_{yd}, σ_{ys}, σ_u and ϵ_{st} reduce but E_{st2} increases.

4. SUMMARY AND CONCLUSIONS

The following observations are based on tests and studies of A572 (Grade 65) Steel, representing a total of fifty-two tests on tension specimens cut from 1/4", 3/8" and 1/2" plates and from eight shapes varying in weight from 19 lbs/ft. to 88 lbs./ft.

1. A572 (Grade 65) steel exhibits mechanical properties in the inelastic region that are similar to those of structural carbon steel. (Fig. 7)

2. The results of this test series conform to the relevant ASTM A572 requirements.

3. The use of E_{st2} as the strain-hardening modulus represents a new approach to obtain a more realistic value of this property for use in situations where the material is assumed to be strained into the strain-hardening range. By eliminating the erratic initial portion of the strain-hardening range of the stress-strain curve and restricting the measurement to the linear portion, E_{st2} provides values which are more conservative and are less subject to scatter.

4. The average value of E_{st2} is 553 ksi which compares favorably with the value of 572 ksi for A7 steel since the latter value is between the values of E_{st2} and E_{st3}. See Fig. 7. This would indicate that the limits on the width-thickness ratios of shapes and the bracing spacing requirements would not be too restrictive This is fortunate, since the A572 (Grade 65) steel is limited to shapes of Group 1 with high width-thickness ratios so that a low value of E_{st} would render most of them non-compact.[2,5]

5. A re-examination of the practice of obtaining the strain-hardening modulus from tension tests is indicated. The value in compression tests is known to be higher than in tension and since this property is associated with failure in compression, a compression test would appear to be the appropriate way of obtaining its value. Unfortunately, the latter test is more difficult to perform.

6. A crosshead speed of 0.025 ipm gave an average value of 44 microin./in./sec. for the strain rate $\dot{\epsilon}$. At this strain rate, the observed value of the dynamic yield stress level was on an average 4% higher. This indicates excellent agreement with projected results of a previous study of the effect of strain rate.[12]

7. The average value of σ_{ym} from mill data is 70.5 ksi and the average percent elongation is 18.3. The average value of the difference between the mill value of σ_{ym} and the corresponding value of σ_{ys} in the current series of tests was 9.3 ksi compared to a value of 4.2 ksi from projection of the results of Ref. 12. The difference is probably due to the fact that the mills often report the upper yield point for the value of σ_{ym}.

8. The average values for σ_{ys} and σ_u for material A were somewhat higher than for material B in spite of the fact that the material A specimens were thicker. The inference is that the material B was probably on the low side of mill distribution.

9. No significant relationship could be established between mechanical properties and the presence or absence of yield lines. This suggests that the mill straightening practice (gagging or rotarizing) is not a significant factor in evaluating these properties.

10. The values of σ_{yd}, σ_{ys} and σ_u reduce and the values of E_{st2} and the Percent Reduction of Area increase with increasing thickness. A similar tendency was noted with respect to increasing weight of shape.

11. The results of this test series show that from a "mechanical property" stand point, it is appropriate to extend plastic design to include A572 (Grade 65) Steel.

5. NOMENCLATURE

Symbols

A_o	=	Original area of the cross section of the specimen
A_f	=	Reduced area at fracture of the specimen
E	=	Young's modulus, ksi, taken as 29,600 ksi
E_{st}	=	Strain-hardening modulus, ksi
E_{st1}	=	Value of E_{st} in ksi obtained from the maximum initial slope of the autographic recorder curve at the apparent onset of strain hardening, judged by eye.
$E_{st1(a)}$	=	Value of E_{st} in ksi determined by curve fitting and used in Ramberg-Osgood stress-strain equation with three parameters.
$E_{st1(b)}$	=	Value of E_{st} in ksi determined using static stress levels at ϵ_{st} and $\epsilon_{st} + 0.002$
E_{st2}	=	Value of E_{st} in ksi obtained as the chord slope of the autographic recorder curve between strain increments 0.003 and 0.010 after the apparent onset of strain-hardening.
$E_{st3(a)}$	=	Value of E_{st} in ksi obtained by the method of least squares from the autographic recorder curve by selecting two strain intervals of 0.065 each after the onset of strain-hardening.
$E_{st3(b)}$	=	Value of E_{st} in ksi determined in the same way as $E_{st3(a)}$ from readings taken from the dial gage and the corresponding readings of the load indicator.
g_o	=	Original gage length
g_f	=	Final gage length after fracture
R_m	=	Maximum rotation capacity
r_y	=	Weak-axis radius of gyration
t	=	Thickness of the specimen; with subscripts as in Fig. 23
w	=	Width of the specimen; with subscripts as in Fig. 23

ϵ	=	Strain
$\dot{\epsilon}$	=	Strain rate, micro in./in./sec.
ϵ_y	=	Strain at first yield, evaluated as σ_{ys}/E
ϵ_{st}	=	Strain at onset of strain-hardening
σ_p	=	Limit of proportionality in ksi as determined by an offset of 0.0001 in./in.
σ	=	Stress, ksi
σ_y	=	Yield stress, ksi stress
σ_{uy}	=	Upper yield point, ksi
$\sigma_{\ell y}$	=	Lower yield point, ksi
σ_{yd}	=	Dynamic yield stress level, ksi
σ_{ys}	=	Static yield stress level, ksi
σ_{ym}	=	Yield stress level in a mill test, ksi
σ_u	=	Tensile strength (ultimate strength), ksi
σ_f	=	Fracture stress, ksi

<u>ABBREVIATIONS</u>

AISC	=	American Institute of Steel Construction
ASTM	=	American Society for Testing and Materials
CRC	=	Column Research Council
ipm	=	inches per minute
ksi	=	kips per square inch

G L O S S A R Y

GENERAL TERMS

Mechanical Properties - Those properties of a material that are associated with elastic and inelastic reaction when force is applied or that involve the relationship between stress and strain.[10]

Strain - The unit change, due to force, in the size or shape of a body referred to its original size or shape. Strain is a non-dimensional quantity but it is frequently expressed in inches per inch.[10]

Stress - The intensity at a point in a body of the internal forces or components of force that act on a given plane through the point. In this report, stress is always expressed in kips per square inch of original area.[10]

TERMS RELATING TO TENSION TESTING

Ductility - The ability of a material to deform plastically before fracturing. Usually evaluated by elongation or reduction of area.[10] Sometimes evaluated by uniform strain.[9] Also related to ϵ_{st}.

Extensometer - A device for measuring linear strain.[10]

Elongation - The increase in gage length after fracture of a tension test specimen usually expressed as a percentage of original gage length. In reporting values of elongation, the gage length shall be stated.[10]

Fracture Stress - Stress, computed as the quotient of the force at the instant of fracture and the original area.

Gage Length - The original length of that portion of the specimen over which strain is determined.[10]

Necking - The localized reduction of the cross-sectional area of a specimen which may occur during stretching.[10]

Proportional Limit - The greatest stress which a material is capable of sustaining without any deviation from porportionality of stress to strain.[10] In this report, measured with an offset of 0.001 in./in. on the stress-strain curve.[8]

Reduction of Area - The difference between the original cross-sectional area of a tension test specimen and the area of its smallest cross-section after fracture. The reduction of area is usually expressed as a percentage of the original cross-sectional area of the specimen.[10]

Relaxation - Decrease in stress at a constant total elongation.[9]

Strain-hardening - Increase in resistance to deformation after the material has undergone finite strain at a practically constant stress subsequent to yielding.

Strain-hardening Modulus - Ratio of increase in stress to increase in strain, usually measured over a finite strain in the strain-hardening range of the stress-strain curve.

Tensile Strength or Ultimate Strength - The maximum tensile stress which a material is capable of sustaining. Tensile strength is calculated from the maximum load during a tension test carried to rupture and the original cross sectional area of the specimen.[10]

Uniform Strain - Strain at maximum load in a tension test.[9]

Yield Point - The first stress in the material less than the maximum attainable stress, at which an increase in strain occurs without an increase in stress.[10] When such increase in strain is accompanied by a decrease in stress, the specimen is said to have recorded an 'upper yield point'. 'Lower yield point' is the lowest stress immediately after the upper yield point is recorded and before the yield stress level stabilizes.

Yield Stress Level - The average stress during actual yielding in the plastic range.[11] For structural steel, the stress remains fairly constant from the yield point up to the level of strain hardening provided the strain rate is held constant. Dynamic yield stress level corresponds to a crosshead speed of 0.025 ipm and the 'static yield stress level' is the yield stress level for zero strain rate. In this report both were measured at a strain of 0.005 in./in. as required by ASTM A370.

Young's Modulus - Ratio of tensile or compressive stress to corresponding strain below the proportional limit.[10]

STATISTICAL TERMS

Average - Sum of n numbers divided by n.

Median - The middlemost value

Standard Deviation - The square root of the average of the squares of the deviation of the numbers from their average. Theoretical estimated percentage of total observations lying within the range of Average ± 1.0 x Standard Deviation is 68.3.

Coefficient of Variation - Ratio of 'Standard Deviation' to 'Average' expressed as a percentage.

APPENDIX

TENSION TESTING PROCEDURE

Table of Contents

1. Equipment Required

2. Preparing the Specimen

3. Preparing the Machine

4. Instrumentation

5. Running the Machine and Recording

6. Measurements on the Fractured Specimen

7. Computations and Data Sheets

8. Condensed Sequence

1. EQUIPMENT REQUIRED

1. 120 kip T.O. Machine with the following accessories:
   a. Flat wedge grips
   b. Grip lines
   c. Grip retainers with connecting bolts and grip spreaders with screws.
   d. Grip cranks
   e. 8" gage autographic extensometer complete with the recorder.
2. 8" Extensometer with a mechanical dial gage.
3. A pair of calipers
4. 0"-1" and 1"-2" micrometers
5. Four pieces of shock-cord, each about 15" long
6. Scriber and center punch
7. Autographic recorder sheets of appropriate load range.
8. Automatic timing device.
9. 12" scale with 100 divisions to an inch
10. Lead hammer
11. Light wooden or cardboard box
12. Rags for cleaning
13. Wax

2. PREPARING THE SPECIMEN

2.1 FABRICATION

1. Order the specimen to be cut to the shape shown in Fig. 18 and milled to a thickness of 1/4" or even less for high strength steels so that the 24 kip range can be used right up to the strain-hardening range of interest.

The recommended shape of the specimen conforms to the minimum standards set by ASTM A370.[10] However, the length of the grip section is increased to 5" from the ASTM minimum of 3". This is done to provide adequate gripping even for the harder materials and to afford greater clearance for the instruments. The minimum fillet radius of 1 in. is increased to 2 in. to take advantage of the currently available equipment at Fritz Laboratory. Milling of the specimen is expected to provide a good surface for gripping and for the knife edge of the autographic extensometer while a thin specimen enable testing on a lower range to obtain greater accuracy.

2.2 PREPARING THE FACES

2. If the faces of the specimen are milled, wipe them clean with rags and proceed to the next step. If not, clean them thoroughly with light mineral oil and remove all loose mill scale. Remove all tight mill scale from the gripping ends by grinding. This mill scale which is usually very hard prevents the grips from biting deep into the parent metal and at higher loads, separates and acts like a lubricant causing the specimen to slip. Remove also any end burrs by

grinding. These end burrs often interfere with gripping. Remove by grinding lightly the mill scale in the area where the knife edge of the autographic extensometer is expected to rest. This is about four inches from the center of the specimen. The thin film of mill scale, if not removed, becomes loose after yielding and may cause the knife edge to slip.

2.3 SCRIBE LINES AND PUNCH MARKS

3. On the front face on which the mechanical dial gage will be mounted, mark the center of the gage length and the center line of the 1 1/2" width of the specimen by means of a scriber. Using this center line, mark scribe lines at every inch up to 4" on each side as shown in Fig. 19. Make sure that the end scribe lines fall within the straight reduced portion of the specimen.

4. Starting from the top end, mark eight punch marks using a center punch. Next, place the mechanical dial gage on the front face of the specimen with the fixed concial point of the dial gage engaging the top punch mark. Push the movable bar so as to obtain the minimum distance between the concial points and draw an arc on the specimen with the lower concial point. The ninth punch mark must lie beyond this arc. This precaution is to ensure free movement of the concial point and prevent any lost motion due to the gage length being smaller than the minimum distance between the concial points. Make the ninth punch mark and verify that the corresponding dial gage reading is greater than the minimum reading.

5. On the rear face of the specimen, make punch mark at the top to match the top punch mark on the front face. The concial point of the autographic extensometer will engage this punch mark.

2.4 MEASUREMENT OF CROSS SECTIONAL DIMENSIONS

6. Using micrometers, measure and record the width and thickness of the specimen at all the nine scribe marks. Also measure and record the gage length of the front face correct to 0.01 in.

2.5 INSPECTION FOR YIELD LINES

7. Inspect both faces of the specimen for yield lines due to straightening in the mill and record definitely the presence or absence of such yield lines. Record the pattern of yield lines on the data sheet making additional sketches if necessary to indicate the corresponding edges.

3. PREPARING THE MACHINE

3.1 CHECKING THE MACHINE

1. Switch on the machine with the main switch at the bottom of one side of the console. After a few minutes, the red light at the control lights up indicating that the machine is warmed up and ready for operation.

2. Set the speed selector to zero. Turn and set the control wheel firmly but not too tightly into the 'SLOW' position. Press the 'LOWER' knob and rotate the speed selector gradually to increase speed until the lower crosshead visibly moves. Lower the lower crosshead until there is a clear distance of at least 10" between the crossheads. Set the speed selector to zero.

This step is to ensure that the machine is in proper working order and also to prevent jamming of the lower crosshead which sometimes occurs when it is suddenly moved at a high speed.

3. The loading speeds change with the aging of the electrical components and when a large number of tests are to be performed or where accurate speed is essential, it may be worthwhile checking the accuracy of the speed selector. To do this, run the machine at no load and measure the rate of separation of crossheads by a dial gage. The machine is built to maintain nearly the same crosshead speed under load.

3.2 ADJUSTMENT OF CROSSHEAD POSITIONS

4. Bring both the crossheads into a convenient working position. The position of the lower crosshead can be adjusted simply by manipulating the controls but the position of the upper crosshead must correspond to a set of pair of slots in the columns. To adjust the position of the upper crosshead, first turn and set the control wheel firmly but not too tightly into the 'FAST' position. Lift the steel collars and remove the split rings from all the four corners of the top of the upper crosshead. Insert the four lifting pins in the holes on the top of the lower crosshead. Push the 'STOP' and then the 'RAISE' button.

It is a good practice to push the 'STOP' button before pushing the 'LOWER' or the 'RAISE' button. This will eliminate the possibility of sudden reversal and damage of the machine. When it is desired to move the lower crosshead in one direction only, use the speed selector for stopping, starting and running it.

Always set the control wheel firmly but not too tightly in the extreme positions of 'SLOW' and 'FAST'. Also, never raise the upper crosshead without removing the upper split rings.

5. Set the speed selector to 1 in. per min. and raise the lower crosshead until the lifting pins touch the upper crosshead and lift it by about an inch. Remove the split rings at the four corners of the bottom of the upper crosshead.

6. Next raise or lower the crossheads until the upper crosshead is about an inch above the slots in the columns corresponding to the desired position of the upper crosshead. Insert the split rings in these slots at the bottom corners of the upper crosshead and lower

the crossheads until the upper crosshead sits firmly on the split rings. Insert the split rings at the top four corners and cover them with the steel collars. Remove the lifting pins. Lower the lower crosshead until the clear distance between the crossheads is about eleven inches.

3.3 INSTALLING GRIPS AND RELATED ACCESSORIES

7. Examine the grips and note how far the gripping surface extends on the length of the grips. If the gripping surface does not extend fully, note the distance by which the surface is recessed from the edge. For best results, the entire length of the gripping surface should be utilized in gripping the specimen.

Using rags, clean thoroughly the flat wedge grips, the liners and the crosshead holes in which grips are housed. Wax the liners and wax the grips on their smooth sides. This will reduce the possibility of the specimen jamming between the grips. Usually, the specimen comes out loose with the shock of fracture but in the absence of fracture, waxed surfaces of the grips and liners are a great help in removing the specimen from the grips.

8. Mount a grip spreader with screws in each of the crosshead holes. The grip spreaders keep the grips apart and facilitate insertion of the specimen. See Fig. 20.

9. Mount a grip retainer under each crosshead using connection bolts. The lip of the grip retainer should be at the top touching the soffit of the crosshead so that the grips cannot slide below the soffit of the crosshead. This will prevent grips from slipping so far down as to get disengaged from the pinion. See Fig. 20.

10. Introduce the grips from the top of each crosshead and adjust them using the grip cranks until they move smoothly and in one level. Mount a grip retainer at the top of the upper crosshead as in Fig. 20. The lip should again be at the top to permit free vertical movement of the grips but prevent their popping out at fracture.

3.4 INSTALLING THE SPECIMEN

11. Introduce the specimen from the top of the upper crosshead after verifying the correct positions of the top and bottom ends as well as the front and rear faces. Lower the specimen until the lower end passes snugly between the grips in the lower crosshead. Introduce liners from the top of the upper crosshead. Provide the liners in pairs and in such numbers and thickness that the grips when locked recess at least 1/2 in. from the soffit of the upper crosshead. See Fig. 21. This minimum distance ensures that the grips and the crosshead do not get overstressed. If the grips are recessed more, the clearance for mounting the instruments or the grip length of the specimen will be reduced. Make sure that the arms of the liners sit firmly on the top of the upper crosshead.

12. Adjust the specimen vertically so that the level of the top of the specimen is flush with the level of the gripping surface. See Fig. 21.

13. Center the specimen visually with respect to the grips and lock the specimen at the top by lightly tapping the grip crank handle with the lead hammer. Always use the lead hammer for this to reduce shock on the pinion and the grip crank.

14. Stand at some distance from the machine and check the verticality of the specimen with distant vertical objects like columns. If the specimen requires a little adjustment, tap the bottom end lightly with the hammer while holding the top in a temporarily locked position.

15. Introduce from the top, into the lower crosshead, the same member and thickness of liners as used in the upper crosshead. The grips when locked must now recessabout 1/2" below the top of the lower crosshead. Adjust the level of the lower crosshead so that the bottom end of the specimen is flush with the bottom edge of the gripping surface. See Fig. 21.

16. Check whether there is adequate clearance for mounting the autographic extensometer and the mechanical dial gage.

17. If the clearances are adequate, proceed to lock the specimen If not, remove the liners from the top of the lower crosshead and introduce them from the bottom. Leave a gap of about 1/4" between the arms of the liners and the bottom of the lower crosshead. Although it is more favorable for gripping if the arms of the liners bear firmly on the bottom of the lower crosshead, it is advisable to leave this clearance to prevent jamming of the specimen at high loads. This constitutes serious problem when the specimen does not fracture. It later on, the specimen slips excessively, provide wooden packing in the gap between the arms of the liners and the soffit of the bottom crosshead. The arms of the liners will thus seat more effectively on the crosshead and will be more effective in preventing slipping. In case of jamming, the wooden packing can be easily removed and the liners pushed down with the use of projecting arms to release the specimen.

18. If the clearances for the instruments are still inadequate reduce the gripping length by the same amount at the top and at the bottom. Obtain the maximum gripping length consistent with a proper mounting of the instruments. Figure 22 shows a specimen with both the instruments mounted.

Whenever the lower crosshead has to be moved for these adjustments, take care to release the lower end of the specimen. This will eliminate the danger of stressing the specimen as also the danger of damaging the machine when the lower crosshead is moved up.

19. Lock the specimen firmly by hitting the grip cranks a few times with the lead hammer. Lock the top first unless the liners in the bottom crosshead are introduced from the bottom, in which case, lock the bottom end of the specimen first. This is to prevent the liners of the bottom crosshead from falling down from the shock of hitting the upper grip crank.

3.5 CLEARING THE WEIGHING TABLE

20. Clear the weighing table completely and place the light wooden or cardboard box to receive the fractured specimen and protect the weighing table. Keep the weighing table clear at all times and do not place any accessories there because the load indicator will record this extra load.

3.6 ZEROING THE RANGES

21. Set the range selector knob to the desired load range and set the local pointer to zero. If you expect to use more than one range, zero the load pointer for all such ranges.

22. Turn and set the control wheel firmly but not too tightly to the 'SLOW' position. Set the speed selector to zero and push the 'STOP' and then the 'LOWER' knob.

3.7 GRIPPING THE SPECIMEN

23. Apply gripping pressure by pulling on the grip crank handles by hand and set the speed selector to 0.5 in. per min. When the load pointer begins to register load, keep loading to a value corresponding to about 5 ksi. Be careful not to overload the specimen. Unload, but leave a few pounds of load on. This will ensure that the specimen is still effectively gripped.

If the specimen slips, apply the gripping load at a much higher speed. Chances of overloading are now increased, so attempt this only after some experience on tension testing. However, gripping is more likely to be a problem with the harder and higher strength specimens where, if the specimens are thick enough, overloading will be less of a problem.

4. INSTRUMENTATION

4.1 THE DIAL GAGE (1/10,000 in.)

1. Adjust the dial gage so that when the main pointer is at zero, the pointer measuring hundreds is exactly at 0, 1, 2 --- etc. This is to avoid ambiguities in reading the dial in intermediate positions. Adjust the position of the plunger of the gage by rotating the screw bearing on the plunger so that a very small reading is obtained on the dial. Lock the screw in this position. Make sure that there is no initial lost motion in the gage be pressing the plunger and observing the movement of the main pointer on the dial.

2. Attach the dial gage to the font face of the extensometer using two shock cords one at the top and one at the bottom. Tie the knots so that they are on the sides and not on the rear face of the specimen.

Adjust the cord tension so that it is even on both sides. Make sure that the conical points engage the punch marks effectively. Aline the plane of the dial gage parallel to the face of the specimen.

4.2 THE AUTOGRAPHIC EXTENSOMETER

3. Set the knife edge end to the long arm setting.

4. Plug in the autographic extensometer and switch on the standby switch to roll back the recorder drum to zero position.

5. Set the magnification knob to A, B and C in succession. If there is no significant change in the position of the drum in all these

three positions, it is an indication that the extensometer and the recorder are properly set. If not, a small adjustment in the position of the coil on the extensometer may be necessary. Always keep the pin on the drum clear of the stop pin using the recorder reset. This will ensure that there is no initial lost motion of the knife-edge of the estensometer. If it is found that the pin on the drum cannot be kept clear of the stop pin even with the recorder reset, adjust the position of the Atcotran differential transformer on the extensometer just anough to obtain a small clearance.

6. Shut off the standby switch under the recorder.

7. Attach the autographic extensometer to the rear face of the specimen by two shock cords, one at the top and one at the bottom. These chock cords should not pass over the mechanical dial gage, because this will make proper positioning of both instruments difficult.

Adjust the cord tension so that it is even on both sides. Make sure that the conical point engages the top punch mark firmly. Make sure that the knife edge of the extensometer bears fully on the specimen. This can be done by adjusting the cord tension on both sides of each cord.

8. Switch on the power and standby switches under the recorder.

9. Carefully, lift the knife edge off the specimen and place it back.

10. Rotate the load recording rod, disengage it from the gears behind the load dial, push it to the zero position and turn it to the desired range - half range or full range. Look behind the load dial and make sure that the rod engages the gears satisfactorily and is free to move.

11. Clean the pen, fill it with ink and check for proper flow. Mount the pen in the penholder but keep it clear of the drum. Set to magnification A. This gives a magnification factor of 400 so that with 8" gage, one division of 0.1 in. on the recorder sheet is equivalent to a strain of 0.00025 in./in.

12. Wrap a recorder shut of appropriate load range on the drum and fix it by slipping the metal paper clip over the edges of the drum. Set to zero using the resetting knob. Make sure that the pin on the drum is clear of the stop pin.

13. Mount the timing device and set it to five seconds but do not switch on the power. Check the pen of the timing device for proper flow.

14. Record the initial reading of the mechanical dial gage.

5. RUNNING THE MACHINE AND RECORDING

5.1 CROSSHEAD SPEED

1. Set the maximum pointer to touch the load pointer on the load dial.

2. Push the 'STOP' knob and then the 'LOWER' knob. Set the speed selector to 0.025 in./min. Use this crosshead speed until the specimen is strained well into strain-hardening.

In order to study the behavior of the material under static loads specimens should be tested at zero strain rate. This is not practical and the next best thing would be to test at a uniform low strain rate $\dot{\epsilon}$.[12] Even this is not easy and most screw-power type machines including the 120 kip Tinius Olsen are built to maintain uniform crosshead speeds.

ASTM A370 specifies a maximum crosshead speed of 0.5 in. per. min. for eight inch gage.[10] However, to reduce the effect of strain rate on the behavior of the material, it is desirable to reduce the crosshead speed. The recommended speed of 0.025 in. per minute is the minimum indicated speed on the speed selector and is also the lowest speed at which the machine works smoothly at all loads.

5.2 OBSERVATIONS

3. Record the following:

(a) Dial gage readings after a fixed interval of load. Choose the interval so that 15 to 25 intervals give the yield load. Always tap the dial gage gently a couple of times before taking a reading. This will reduce mechanical lags in the gage.

(b) All slips together with the corresponding loads as indicated by the maximum pointer. Set the maximum pointer back to touch the load pointer immediately after the load is recorded.

(c) Upper yield load, being the load indicated by the maximum pointer when yielding commences and the load drops.

(d) After the yield, record the load for every 0.005 in. of elongation.

(e) Set the maximum pointer back to touch the load pointer and just before the strain attains a value of 0.005 which corresponds to 2 in. on the strain axis of the recorder sheet, reduce the speed gradually until the machine stalls. Do not turn back the speed selector any more than is just necessary to stall the machine. Record the dynamic yield load as indicated by the maximum pointer.

This practice of stalling the motor is strongly recommended in preference to pushing the 'STOP' button or setting the speed selector to zero for two reasons: (i) It eliminates the 'backing up' of the motor and (ii) it averts the danger of pushing a wrong button.

Observe the load dial reading five minutes after stalling the machine. Record this as the static yield load. Also record the mechanical dial gage reading.

(f) Start the machine again setting the speed selector at 0.025 in./min. Read and record the dial gage and load everytime the dial gage pointer is at 0 or 50 on the dial. Stall the machine again at a strain of 0.0125 which corresponds to 5 in. on the strain axis of the recorder sheet. Record the maximum pointer load.

It is necessary to stop the first run in this way in order to obtain the important initial portion of the strain-hardening range of the curve in one run. If the first run is allowed to run for its full length and if the strain-hardening strain is large, the machine will have to be stopped soon after the onset of strain-hardening so that it will be impossible to get any reliable data in in the strain-hardening range. However, if strain-hardening is found to commence at a strain of less than 0.0125, the run must be continued until the strain of 0.025 or 10" on the strain axis is reached.

(g) Lift the pen off the specimen and push the pen assembly out towards the end knob of the load recording rod. This will keep the trace of the second run distinct from the first. Lift the knife edge of the autographic extensometer off the specimen and allow the drum to rotate back. Set the pen back on paper and record the corresponding load from the load pointer and the dial gage reading.

Everytime that the pen is required to be lifted up or set down, turn the end knob of the load recording rod in the direction of the selected range, so that the gear are firmly engaged before rotating the penholder clamp. This will guard against the gears disengaging while the penholder is being rotated.

(h) Set the speed selector at 0.025 ipm and switch on the power for the timing device.

(i) Continue to record the dial gage and load readings at every 0.005 in. of elongation for the full run of the drum.

4. As soon as the end of the recorder sheet is about to be reached, stall the machine, switch off the timing device. Remove the penholder from the clamp and the recorder sheet from the drum. Dismount the mechanical dial gage and the autographic extensometer.

5. Record the ultimate load as the maximum load indicated by the maximum pointer.

6. As the load drops, watch the load pointer carefully. Stay away from the specimen and warn passersby. Observe the load corresponding to the thud of fracture. Record this as the fracture load.

5.3 CHANGE OF RANGE

7. If at any stage of loading, you want to change the load range, simply turn the range selector knob to the desired range. Do not go beyond the capacity of any range. Preferably, change the range when the crosshead speed is zero and record the load in both the ranges. Do not change the range when the autographic recorder output is being obtained. Do not change to a lower range before making sure that the load falls within that range.

5.4 CHECKING THE INSTRUMENTS

8. If a general idea is available about the mechanical properties of the specimen under test, compute the elongation for the interval of load for which the dial gage is read in the elastic range. Also the load-strain curve in the elastic range can be computed. Check these values against the test values as the test proceeds. If no idea of the properties of the specimen is available, observe the functioning of the mechanical dial gage and the autographic extensometer and check that their readings are in broad agreement. One inch on the strain axis of the recorder is equal to an elongation of 0.02 in. on the mechanical dial gage. Correct any malfunctioning of the instruments in the elastic range only. Compare also, the strains computed from the mechanical dial gage with the strains recorded by the autographic recorder at least at two points (i) At static yield load and (ii) At the commencement of the second run on the recorder.

5.5 RELIABILITY OF LOAD DIAL READINGS

9. While taking load readings, always read the load dial. This will give more accurate values. Use the autographic curve only for a check.

5.6 SLIPPING OF THE SPECIMEN

10. If at any time during the elastic range, the specimen slips excessively, unload and dismount the autographic extensometer and the mechanical dial gage. Release the specimen and look for the causes of slip: Mill scale in grips or specimen, inadequate tightening, etc. and after setting right the deflects, start all over again.

5.7 WINDING UP THE TEST

11. Switch off the machine unless another test is immediately planned. Remove the grips, liners, grip spreaders and grip retainers and place them in the storage. Leave the working areas clean. Complete the log book.

6. MEASUREMENTS ON THE FRACTURED SPECIMEN

6.1 POSITION OF FRACTURE

1. Observe the position of the fracture with respect to the punch marks and record on the diagram on data sheet.

6.2 FINAL GAGE LENGTH

2. Place the fractured pieces with the matching surfaces of the fracture close together and the front face up. Measure, up to 0.01 in., using calipers the distance between the gage points and record it as the final gage length.

6.3 CROSS SECTIONAL DIMENSIONS OF THE FRACTURE

3. Measure the width at fracture on both pieces and the thickness at three locations on each piece as indicated in Fig. 23. Measure w_1, t_1, t_2, t_3 on the upper fractured surface and w_2, t_4, t_5 and t_6 on the lower fractured surface.

Record the width and thickness as the average of the corresponding measurements.

6.4 STORAGE OF THE FRACTURED SPECIMEN

4. Identify and retain the fractured pieces until the final submission of the summary report on the project. Classify as scrap later with the permission of the project director.

7. DATA SHEETS AND COMPUTATIONS

A set of data sheets and a set of typical test results are included at the end of this chapter.

A summary of the quantities to be recorded from the test are given below. The terms are defined in the chapter on 'Nomenclature'. A few of the terms are illustrated graphically in Fig. 23.

From the specimen:

1. Thickness and width at nine locations,
2. Original gage length g_o
3. Final gage length after fracture g_f
4. Width at two locations and thickness at six locations on the fractured areas.

From the load dial:

1. Upper yield load (maximum pointer)
2. Dynamic yield load (maximum pointer)
3. Static yield load
4. Load readings corresponding to an elongation of 0.005 in. on the mechanical dial gage up to the end of the second run.
5. Load reading at the commencement of the second run on the recorder
6. Ultimate load (maximum pointer)
7. Fracture load

From the mechanical dial gage

1. Readings corresponding to a fixed increment of load in the elastic range.

2. Reading corresponding to static yield load

3. Reading corresponding to the commencement of the second run on the recorder.

Compute the following:

From the specimen:

1. Average thickness and width. Take their product as the average original area A_o of the cross section.

2. Elongation = $g_f - g_o$

Percent Elongation = 100 x Elongation/g_o

3. Reduced area A_f = Average reduced thickness x average reduced width. Reduction of area = $A_o - A_f$ and Percent Reudction of area = 100 x Reduction of area/A_o

From the Load Dial:

1.. Upper yield stress σ_{uy} = Upper yield load/A_o

2. Dynamic yield stress σ_{yd} = Dynamic yield load/A_o

3. Static yield stress σ_{ys} = Static yield load/A_o

4. Ultimate strength σ_u = Ultimate load/A_o

5. Fracture stress σ_f = Fracture load/A_o

From the load dial and the mechanical dial gage readings:

1. Construct a stress-strain curve in the strain-hardening range and using figure 2, compute strain-hardening strain ϵ_{st} and strain-hardening modulus E_{st} by two approaches: E_{st2} and $E_{st3(b)}$.

2. Strain corresponding to static yield load and the commencement of the second run on the recorder

From the recorder sheet

1. Proportional limit σ_p = Load corresponding to $\Delta\epsilon = 0.0001/A_o$. See Fig. 1.

2. ϵ_{st}, E_{st1} (see Fig. 8), E_{st2}, $E_{st3(a)}$. For computing $E_{st3(a)}$, modify ϵ_{st} to a value obtained by the intersection of the stress-strain curve of the yield stress level in the plateau and the tangent to the curve in the strain-hardening range. This tangent is drawn as the average value in an increment of 0.002 in./in. after the apparent onset of strain-hardening.[8]

TENSION TEST

Date: ______________________ Project ______________

Temperature: ______________________ Spec. No. ______________

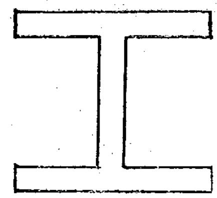
Tested by: ______________________ Shape ______________

Machine used: ______________________

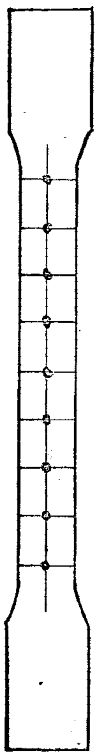
Gages used: ______________________

Scales: ______________________
(Automatic
Recorder)

Crosshead Speed: ______________________



Location of Specimen
in cross section



Measurements	
Thickness (in.)	Width (in.)
(average)	(average)

Any Yield Lines?

Gage Length: ______________ in.

Final Gage Length: ______________ in.

(Average Area): ______________ sq. in.

Indicate Fracture on Sketch.

Measurements on Fracture Surface

w_1 = ______ w_2 = ______

t_1 = ______ t_2 = ______ t_3 = ______

t_4 = ______ t_5 = ______ t_6 = ______

Reduced Area: ______ in. x ______ in.

= ______________ sq.in.

Loads	(Kips)
Upper Yield Load	
Dynamic Yield Load (ϵ = 0.005)	
Static Yield Load (ϵ = 0.005)	
Ultimate Load	
Fracture Load	

RESULTS: (Attach load elongation curve and supporting calculations)

Proportional Limit ($\Delta\epsilon$ = 0.0001)	ksi
Upper Yield Stress	ksi
Dynamic Yield Stress (ϵ = 0.005)	ksi
Static Yield Stress (ϵ = 0.005)	ksi
Ultimate Stress	ksi
Fracture Stress	ksi
Strain at Strain Hardening: Auto:	%
Dial:	%
Percent Elongation	%
Percent Reduction of Area	%

Strain-Hardening Modulus:

Auto:	E_{st1}	ksi
	E_{st2}	ksi
	$E_{st3(a)}$	ksi
Dial:	E_{st2}	ksi
	$E_{st3(b)}$	ksi

Specimen No. ____________

SUPPORTING CALCULATIONS

Original Area = ________ sq. in.

	LOAD (kips)	STRESS (ksi)
Proportional Limit ($\Delta\epsilon = 0.0001$)		
Upper Yield		
Dynamic Yield		
Static Yield		
Ultimate		
Fracture		

Original Length (Gage Length) = __________ in.

STRAINS	ELONGATION (in.)	STRAIN
Strain at Strain Hardening		
Percentage Elongation		

	FINAL AREA (sq.in.)	ORIGINAL AREA (sq. in.)	RECUCTION BY PERCENTAGE
Percentage Reduction of Area			_____(100) = _____%

Specimen No. ______

DIAL GAGE DATA

Load kips	Dial Reading	Extension $\times 10^4$	Strain $\times 10^5$	Remarks

TENSION TEST

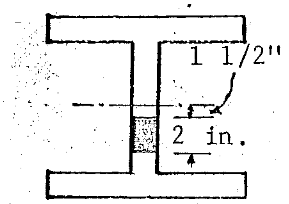
Date:	Sunday, Aug. 25, 1968	Project	343
Temperature:	Room	Spec. No.	4.14.5W
Tested by:	S. Desai & S. Iyengar	Shape	10W54 modified, b=8 3/8"

Machine used: Tinius-Olsen 120 k

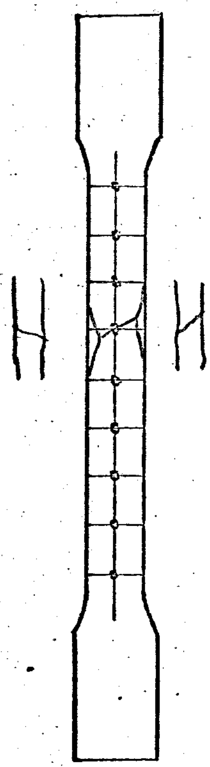
Gages used: Mounted Dial Gage, Autographic Recorder

Scales: (Automatic Recorder) 1 Small Div.= 500 lbs. (Load Axis)
1 Small Div.= 0.00025 in./in.(strain axis)
Long Arm, Magnification A

Crosshead Speed: 0.025 ipm (and see notes)



Location of Specimen in cross section



Measurements

Thickness (in.)	Width (in.)
0.380	1.499
0.380	1.499
0.381	1.501
0.380	1.500
0.380	1.503
0.380	1.503
0.380	1.503
0.381	1.502
0.382	1.500
3.424	13.510
0.380 (average)	1.501 (average)

Any Yield Lines? No

Gage Length: 8.01 in.

Final Gage Length: 9.78 in.

(Average Area): 0.570 sq. in.

Indicate Fracture on Sketch.

Measurements on Fracture Surface

w_1 = 1.144 w_2 = 1.140

t_1 = 0.282 t_2 = 0.253 t_3 = 0.292

t_4 = 0.288 t_5 = 0.262 t_6 = 0.300

Reduced Area: 1.142in. x 0.279in.

= 0.319 sq.in.

Loads	(Kips)
Upper Yield Load	No upper yield
Dynamic Yield Load (ϵ = 0.005)	33.55
Static Yield Load (ϵ = 0.005)	32.50
Ultimate Load	45.90
Fracture Load	35.80

RESULTS: (Attach load elongation curve and supporting calculations)

Proportional Limit ($\Delta\epsilon$ = 0.0001)	53.50	ksi
Upper Yield Stress	---	ksi
Dynamic Yield Stress (ϵ = 0.005)	58.9	ksi
Static Yield Stress (ϵ = 0.005)	57.0	ksi
Ultimate Stress	80.6	ksi
Fracture Stress	62.9	ksi
Strain at Strain Hardening: Auto:	1.345	%
Dial:	1.365	%
Percent Elongation	22.25	%
Percent Reduction of Area	45.2	%

Strain-Hardening Modulus:

Auto:	E_{st1}	4,210	ksi
	E_{st2}	601	ksi
	$E_{st3(a)}$	950	ksi
Dial:	E_{st2}	589	ksi
	$E_{st3(b)}$	1,122	ksi

Specimen No. 4.14.5W

SUPPORTING CALCULATIONS

Original Area = 0.57 sq. in.

	LOAD (kips)	STRESS (ksi)
Proportional Limit ($\Delta\epsilon$ = 0.0001)	30.5	53.5
Upper Yield	--	--
Dynamic Yield	33.55	58.9
Static Yield	32.50	57.0
Ultimate	45.90	80.6
Fracture	35.80	62.9

Original Length (Gage Length) = 8.01 in.

STRAINS	ELONGATION (in.)	STRAIN
Strain at Strain Hardening	53.8 divs.	0.01345
Percentage Elongation	9.78-8.01	22.25

	FINAL AREA (sq.in.)	ORIGINAL AREA (sq. in.)	RECUCTION BY PERCENTAGE
Percentage Reduction of Area	0.312	0.570	$\frac{0.258}{0.570}(100)$ = 45.2 %

Specimen No. 4.14.5W

DIAL GAGE DATA

Load kips	Dial Reading	Extension x 10^4	Strain x 10^5	Remarks
0.25	1208	0		
2	1216	8	10	
4	1223	15	18.75	
6	1233	25	31.25	
8	1243	35	43.75	
10	1253	45	56.25	
12	1263	55	68.75	
14	1272	64	80	
16	1282	74	92.5	
18	1290	82	102.5	
20	1300	92	115	
22	1310	102	127.5	
24	1320	112	140	
26	1330	122	152.5	
28	1340	132	165	
30	1355	147	183.75	
32	1371	163	203.75	
33	1385	177	221.25	
32.50	1644	436	545	
33.55	1700	492	615	
33.55	1750	542	677.5	

DIAL GAGE DATA

Specimen No. 4.14.5W

Load kips	Dial Reading	Extension $\times 10^4$	Strain $\times 10^5$	Remarks
33.55	1800	592	740	
33.55	1850	642	802.5	
33.55	1900	692	865	
33.55	1950	742	927.5	
33.55	2000	792	990	
33.55	2050	842	1052.5	
33.55	2100	892	1115	
33.55	2150	942	1177.5	
33.55	2200	992	1240	
33.50	2250	1042	1302.5	Onset of strain-hardening
32.50	2300	1142	1427.5	
34.2	2400	1192	1490	
34.45	2450	1242	1552.5	
34.75	2500	1292	1615	
35.00	2550	1342	1677.5	
35.20	2600	1392	1740.	
35.45	2650	1442	1802.5	
35.70	2700	1492	1865	
35.95	2750	1542	1927.5	
36.20	2800	1592	1990	
36.35	2850	1642	2052.5	

Specimen No. 4.14.5W

DIAL GAGE DATA

Load kips	Dial Reading	Extension $x\ 10^4$	Strain $x\ 10^5$	Remarks
36.55	2900	1692	2115	
36.75	2950	1742	2177.5	
36.9	2000	1792	2240	
37.1	3050	1842	2302.5	
37.3	3100	1892	2365	
37.5	3150	1942	2427.5	
37.65	3200			
42.50				
42.90				slip (small)

ϵ_{st}: Dial: 0.01365

Auto: 53.8 divns = 0.01345

Auto: E_{st1}: Relative values (29, 18000) and (74, 45000)

$$E_{st} = \frac{27}{45 \times 0.00025} \times \frac{1}{0.57} = 4\,210 \text{ ksi}$$

E_{st2}: Load at ϵ_{st} + 0.003 = 34,900 lbs.

Load at ϵ_{st} + 0.010 = 37,300 lbs.

$$E_{st} = \frac{2400}{0.57} \times \frac{1}{0.007} \text{ psi} = \frac{2400}{7(0.57)} \text{ ksi} = 601 \text{ ksi}$$

$E_{st3(1)}$: Rel. value (41, 31500) and (78, 36500)

$$E_{st3(1)} = \frac{5.0}{37\,(0.00025)} \times \frac{1}{0.57} = 950 \text{ ksi}$$

Dial: E_{st2}: ϵ_{st} = 0.01365; ϵ_{st} + 0.003 = 0.01665; ϵ_{st} + 0.010 = 0.02365

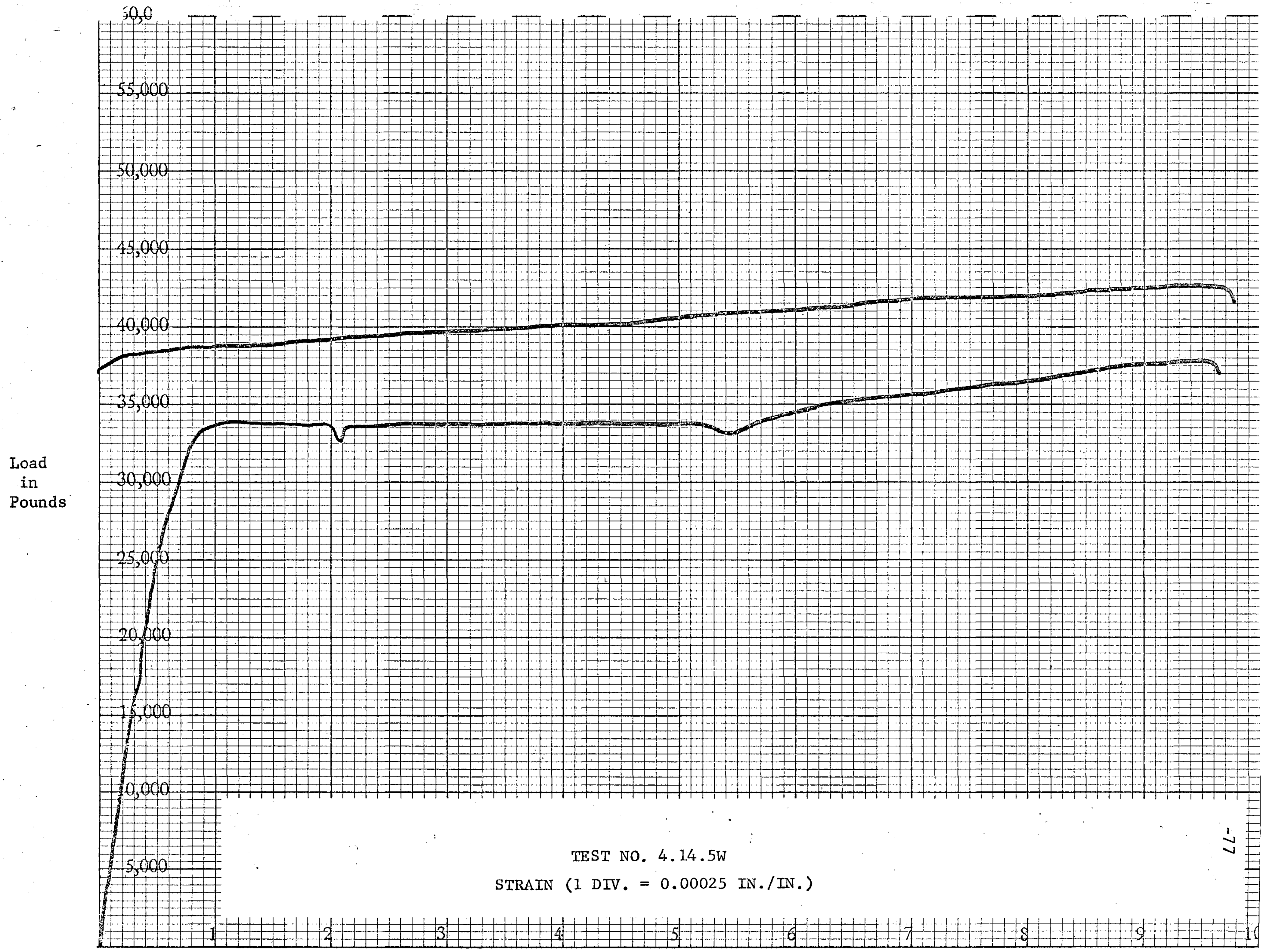
Loads $34.75 + 0.25\,\frac{50}{62.5} = 34.95$; 37.3

$$E_{st2} = \frac{2.35}{0.07 \times 57} = 589 \text{ ksi}$$

$E_{st3(2)}$ Load at ϵ_{st} + 0.005 = 35.70

$$E_{st3(2)} \quad \frac{35.70 - 32.50}{0.57 \times 0.005} = \frac{0.64(1000)}{0.57} = 1122 \text{ ksi}$$

NOTES: The specimen did not exhibit upper yield point. A small slip occurred at a load of 42.90 k (after the second run on paper). At the end of the second run on paper, speed was increased to 0.050 ipm. After the ultimate load, (when load began to drop), at a load of 45.3 k, speed was further increased to 0.100 ipm.



TEST NO. 4.14.5W

STRAIN (1 DIV. = 0.00025 IN./IN.)

8. CONDENSED SEQUENCE

A brief summary of the various steps involved is now given. Since the tension test is best conducted by a group of two workers, the recommended subdivision of the work between the two, designated A and B is also indicated

	A	B

8.1 EQUIPMENT REQUIRED

1. Collect the required equipment and the accessories

8.2 PREPARING THE SPECIMEN

2. Clean and grind the specimen. See Fig. 19

3. Make scribe lines and punch marks. See Fig. 19

	A	B
4.	Measure thickness, width and g_o	Record the measurements taken by A.
5.		Look for yield lines and record.

8.3 PREPARING THE MACHINE

	A	B
6.	Clean the crosshead holes, grips and gripliners. Wax the gripliners and the grips. Install the grip spreaders and the grip retainers. See Fig. 20.	Check the working of the machine. Bring the crossheads into a convenient working position. Install the grips.
7.	Install the specimen and the gripliners. Adjust the total thickness of gripliners, position of specimen and lower crosshead to obtain conditions shown in Fig. 21. Aline the specimen.	Manipulate the grip crank to hold and release the specimen while A adjusts to the position shown in Fig. 21. Check the position and alinement of the specimen. Check the position of grips. Check the clearance for the instruments.

	A	B
8.	Clear the weighing table. Place the light box on it	Pull the grip crank handles and hit lightly with lead hammer to lock the specimen. Zero the desired load range.
9.	Keep pulling	Run the machine to grip the specimen. Unload.

8.4 MOUNTING THE MECHANICAL DIAL GAGE

10.	Tie the shock cords. Equalize the cord tension and aline the gage parallel to the specimen	Hold the mechanical dial gage in position on the front face of the specimen.
11.		Check that the conical points engage the punch marks satisfactorily. Check the alinement of the gage.

8.5 MOUNTING THE AUTOGRAPHIC EXTENSOMETER

12.	Check that the knife edge has long arm setting. Plug in the extensometer.	Switch on the power and standby switches. Check the zero error and the working of the recorder reset. Switch off the standby switch.
13.	Tie the shock cords. Adjust cord tension to secure full bearing of the knife edge on the specimen.	Hold the extensometer in position on the rear face of the specimen.
14.		Check that the top conical point engages the punch mark satisfactorily. Check that the knife edge bears fully on the specimen Switch on the standby switch.
15.	Lift the knife edge off the specimen and place it back.	Zero the load recording rod and set to the desired range. Set the magnification knob to A.

	A	B
16.	Mount the timing device. Check the pen for proper flow.	Fix and zero the recorder sheet.
17.		Mount the pen assembly and check the pen for proper flow.
18.	Check the position of the load recording rod behind the load dial.	

8.6 RUNNING THE MACHINE AND RECORDING

	A	B
19.	Read and record the initial reading of the dial gage.	
20.		Run the machine at a crosshead speed of 0.025 ipm.
21.	List the values of loads at which readings are to be taken in the elastic range.	
22.	Read and record the dial gage reading against the corresponding load when B calls 'Read'	Call 'Read' as soon as a value listed in step 21 is reached.
23.	Read every slip and the minimum reading after every slip. Record loads read by B.	At every slip, read the load from the maximum pointer and the minimum load after slip.
24.	Check approximately the agreement between the mechanical dial gage and the autographic extensometer.	
25.	Record the upper yield load	Read the upper yield load from the maximum pointer. Set back the maximum pointer to touch the load pointer.
26.		Just before the strain is about to reach 2 in. on the strain axis of the graph, stall the machine.

	A	B
27.	Record the dynamic yield load and the static yield load. Read and record the dial gage reading corresponding to the static yield load. Check that the elongation on the dial gage is about 0.04 in.	Read the dynamic yield load from the maximum pointer. Wait for five minutes after stalling the machine and read the static yield load.
28.		List values differing by 50 divisions on the dial gage.
29.	Call 'Read' everytime the dial gage reaches a value listed in step 28.	Read and record the load against the corresponding listed value when A calls 'Read.'
30.	Read the dial gage at each slip and read the minimum value after each slip.	Read and record the load at each slip and the minimum load after each slip. Also record the dial gage readings of A.
31.		Stall the machine at about 5 in. on the strain axis. From the maximum pointer, read and record the corresponding load. Lift the pen off the recorder sheet.
32.	Lift the knife edge off the specimen for a few seconds to allow the drum to roll back completely.	Push the pen assembly out on the load recording rod. Set the pen back on paper.
33.	Read the dial gage	Read and record the load. Record the dial gage readings of A. Run the machine again at a crosshead speed of 0.025 ipm.
34.	Call 'Read' everytime the dial gage reaches a value listed in step 28.	Read and record the load against the corresponding listed value when A calls 'Read'

	A	B
35.	Near the end of the second run, take off the dial gage.	Switch off the standby switch. Lift the pen off the recorder sheet.
36.	Take off the autographic extensometer.	
37.	Read and record the ultimate load.	
38.	Read and record the fracture load.	

8.7 MEASUREMENTS ON THE FRACTURED SPECIMEN

	A	B
39.		Observe and sketch the position of the fracture on the data sheet.
40.	Match the fractured surfaces closely and measure g_f.	Record g_f
41.	Measure w_1, w_2, t_1, t_2, t_3, t_4, t_5 and t_6. See Fig. 23.	Record the values measured by A

8.8 COMPUTATIONS

42. Compute average thickness, average width and A_o

43. Compute σ_{uy}, σ_{yd}, σ_{ys}, σ_u and σ_f

44. From mechanical dial gage readings, compute ϵ_{st}, E_{st2} and $E_{st3(b)}$.

45. From autographic extensometer, compute σ_p, ϵ_{st}, E_{st1}, E_{st2} and $E_{st3(a)}$

46. Compute A_f and Percent Reduction of Area.

47. Compute Percent Elongation.

Table 1: Proposed Program of Work Under Project 343

PLASTIC DESIGN

AND THE

PROPERTIES OF 65 ksi STEEL

Phase	Purpose	Tests
1. Mechanical Properties (Fritz Lab)	Determine E_{st}, ε_{st}, as well as σ_y, E, σ_u, v, % elongation, for variety of shapes and plates.	Coupon type tests Flange and web, Shapes and Plates thick and thin. (Include a few simulated mill tests) V65 and Exten 65. A few compression tests.
2. Mechanical Properties (Producers)	Collect such preliminary information as is available is producers' research labs on properties listed in Phase 1.	None (Producers supply typical complete σ - ε curves)
3. Mill data	Find statistical variation in σ_y and such other properties as are reported in the mill test sheet.	None Producers supply Mill reports for a "few thousand" specimens
4. Stub Column Tests	Check local buckling to verify theory (observe proportional limit) observe average yield stress.	2 tests (one heavy, one light)
5. Beam tests	Check local buckling provision, check lateral bracing spacing provision, check shear rule	3 tests "Beam" shapes, moment gradient and uniform moment.
6. Beam Column	Check Column provisions of theory	1 test (Some material as one of Phase 4 tests)
7. Residual Stresses	Needed for beam column theory (check stub column test, local and lateral buckling in ASD)	Several sets same as Phase 4

TABLE 2: SUMMARY OF RELEVANT ASTM STANDARDS[2]

Chemical Requirements (All Figures for Check Analysis)

	Carbon Max %	Manganese %	Phosphous Max %	Sulfur Max %	Silicon Max %	Copper Min.%
A36	0.30	--	0.05	0.063	**	0.18*
A242	0.21	Max 1.30	--	0.063	--	--
A440	0.32	1.05-1.65	0.05	0.063	0.33	0.18
A441	0.26	Max 1.40	0.05	0.063	0.33	0.18
A572						
Grade 42	0.25	Max 1.40	0.05	0.06	0.35	0.18*
Grade 45	0.26	"	"	"	"	"
Grade 50	0.27	"	"	"	"	"
Grade 55	0.39	"	"	"	"	"
Grade 60	0.30	"	"	"	"	"
Grade 65	0.30	"	"	"	"	"

* Only when specified by customer
** 0.13 to 0.33 for shapes over 426 lb/ft and plates over 1 1/2 in. thick.

These are broad requirements only. A572 also details the alloying combination as one of the following alternatives.

(1) Columbium: 0.004 to 0.06%

(2) Vanadium: 0.005 to 0.11%

(3) Columbium (0.05% max) + Vanadium = 0.01 to 0.11%

(4) Nitrogen (with Vanadium) = 0.015% max. Minimum ratio of Vanadium to Nitrogen = 4:1

Tensile Requirements and Maximum Product Thickness

	Minimum σ_y, ksi	Minimum σ_u, ksi	Minimum Percent Elongation (8 in. gage)	Max. Thickness or Size Plate & Bars	Shapes
A36	36	58	20	--	--
A242, A440,	50	70	18	up to 3/4"	Group 1 & 2
A441	46	67	19	over 3/4" to 1/2" incl.	Group 3
	42	63	16	over 1 1/2" to 4" incl.	Group 4 & 5
A572	42	60	20	4	All shapes up to 426 lb/ft. incl.
	45	60	19	1 1/2	
	50	65	18	1 1/2	
	55	70	17	1 1/2	
	60	75	16	1	Group 1 & 2
	65	80	15	1/2	Group 1

TABLE 3: PROGRAM OF TESTS

Material	Heat Number	Number of Specimens
A	69347*	2-from web of 16W71 2-from flange of 16W71 2-from web of 16W88 2-from flange of 16W88
B	12T3271	3-from 1/2" plate 4-from 3/8" plate 4-from 1/4" plate
	144T393	2-from web and 2-from flange of 10W39
	155S625	2-from web and 1-from flange of 12W36
	145S623	2-from web and 2-from flange of 16W36
	154S527	2-from web and 2-from flange of 14W30
	144T337	2-from web of 16B26 2-from flange of 16B26
	145V569*	2-from web and 4-from flange of 10W54 stub columns
	141T414	2-from web and 2-from flange of 12B19 2-from web and 2-from flange of end of 12B19 beam previously tested under moment gradient.
Total		52

* Shapes outside of Group 1, ASTM A6[2].

TABLE 4: TEST SPECIMENS

Material	Test.No.	Section inxin.	Shape	Condition of Specimen
A	1.1.1W	0.527x1.591	web-16W88	Clean
"	1.1.2W	0.550x1.592	"	"
"	4.13.1W	0.509x1.596	web-16W71	"
"	4.13.2W	0.521x1.594	"	"
"	1.1.3F	0.819x1.593	flange-16W88	"
"	1.1.4F	0.820x1.591	"	"
"	4.13.3F	0.809x1.595	flange-16W71	"
"	4.13.4F	0.817x1.594	"	"
B	1.7.1P	0.524x1.503	plate	Clean
"	1.7.2P	0.522x1.504	"	"
"	1.7.3P	0.521x1.501	"	"
"	1.9.1P	0.404x1.493	"	"
"	1.9.2P	0.403x1.494	"	"
"	1.9.3P	0.402x1.493	"	"
"	1.9.4P	0.402x1.503	"	"
"	1.11.1P	0.256x1.505	"	"
"	1.11.2P	0.256x1.499	"	"
"	1.11.3P	0.255x1.501	"	"
"	1.11.4P	0.254x1.503	"	"
B	1.2.1W	0.340x1.501	web-10W39	Yield lines
"	1.2.4W	0.339x1.501	"	Clean
"	1.3.1W	0.338x1.500	web-12W36	"
"	1.3.2W	0.338x1.501	"	"
"	1.4.1W	0.307x1.502	web-16W36	"
"	1.4.3W	0.323x1.504	"	"
"	1.5.1W	0.274x1.500	web-14W30	"
"	1.5.2W	0.273x1.503	"	"
"	1.6.1W	0.293x1.503	web-16B26	"
"	1.6.2W	0.284x1.498	"	"
"	4.14.2W	0.380x1.501	web-10W54	"
"	4.14.5W	0.380x1.501	"	"
"	5.15.1W	0.257x1.510	web-12B19	"
"	5.15.2W	0.259x1.501	"	"
"	5.15.5W	0.262x1.504	"	"
"	5.15.6W	0.265x1.505	"	"
B	1.2.2F	0.516x1.500	flange-10W39	Yield lines
"	1.2.3F	0.513x1.503	"	Clean
"	1.3.3F	0.527x1.511	flange-12W36	"
"	1.4.2F	0.427x1.502	flange-16W36	Yield lines
"	1.4.4F	0.424x1.552	"	Clean
"	1.5.3F	0.390x1.500	flange-14W30	Yield lines
"	1.5.4F	0.383x1.503	"	Clean
"	1.6.3F	0.359x1.500	flange-16B26	Yield lines
"	1.6.4F	0.371x1.500	"	Clean
"	4.14.1F	0.641x1.499	flange-10W54	"
"	4.14.3F	0.628x1.500	"	"
"	4.14.4F	0.611x1.500	"	"
"	4.14.6F	0.637x1.503	"	"
"	5.15.3F	0.368x1.502	flange-12B19	"
"	5.15.4F	0.367x1.495	"	"
"	5.15.7F	0.371x1.506	"	"
"	5.15.8F	0.372x1.505	"	"

TABLE 5: OBSERVED STRESS (ALL VALUES IN ksi)

Material	Test No.	Proportional Limit σ_p	Upper Yield σ_{uy}	Dynamic Yield σ_{yd}	Static Yield σ_{ys}	Ultimate σ_u	Fracture σ_f
A	1.1.1W	47.7	64.4	62.1	60.7	86.8	67.4
"	1.1.2W	57.1	--	63.9	61.3	87.4	79.3
"	4.13.1W	30.8	66.0	64.8	62.6	88.0	67.2
"	4.13.2W	48.2	64.6	64.3	61.0	85.6	65.7
"	1.1.3F	61.4	70.5	67.3	65.0	*	--
"	1.1.4F	35.6	64.6	64.8	63.1	*	--
"	4.13.3F	46.4	--	64.2	62.2	89.6	68.6
"	4.13.4F	53.8	69.2	65.9	63.7	*	--
B	1.7.1P	63.5	65.7	63.6	62.8	87.0	67.9
"	1.7.2P	63.1	63.9	62.5	60.5	86.2	66.2
"	1.7.3P	38.4	66.4	63.0	60.9	87.0	62.6
"	1.9.1P	64.1	65.6	62.7	60.7	86.7	67.6
"	1.9.2P	65.6	66.5	62.8	60.2	85.0	66.8
"	1.9.3P	67.3	67.3	64.1	61.6	87.2	68.2
"	1.9.4P	58.0	67.5	63.9	62.1	86.3	67.0
"	1.11.1P	67.5	69.3	66.9	63.9	86.4	69.9
"	1.11.2P	66.6	71.3	66.6	62.7	87.5	71.3
"	1.11.3P	68.8	71.6	68.5	65.6	87.7	70.8
"	1.11.4P	72.0	72.0	68.2	63.6	82.0	70.2
B	1.2.1W	61.9	64.0	61.9	59.0	82.6	64.6
"	1.2.4W	53.0	63.7	62.1	60.4	83.6	66.7
"	1.3.1W	68.3	68.4	65.3	63.4	86.5	71.5
"	1.3.2W	67.9	67.9	65.7	63.6	86.4	70.6
"	1.4.1W	66.4	68.1	65.5	63.6	86.5	68.1
"	1.4.3W	62.4	65.0	65.2	62.5	84.7	71.2
"	1.5.1W	69.3	70.6	67.9	65.0	86.4	71.5
"	1.5.2W	55.2	66.4	65.7	60.3	83.3	68.4
"	1.6.1W	58.9	--	63.5	60.5	83.9	65.2
"	1.6.2W	47.1	63.1	63.1	60.0	82.8	71.5
"	4.14.2W	60.9	62.1	60.6	58.7	81.7	64.8
"	4.14.5W	54.0	--	58.9	57.0	80.6	62.9
"	5.15.1W	67.0	69.4	68.5	65.2	87.8	70.4
"	5.15.2W	68.5	69.8	68.5	64.4	87.8	72.1
"	5.15.5W	66.2	68.7	67.7	65.4	87.8	71.0
"	5.15.6W	62.7	68.2	66.7	64.4	86.7	70.7
B	1.2.2F	58.2	66.8	65.9	63.8	87.4	65.9
"	1.2.3F	52.5	--	65.9	64.2	89.3	71.5
"	1.3.3F	62.6	64.5	62.9	60.3	83.4	64.6
"	1.4.2F	42.9	--	61.4	58.3	83.2	64.6
"	1.4.4F	53.1	--	60.4	58.8	80.4	61.1
"	1.5.3F	38.5	65.2	64.2	62.2	84.2	67.2
"	1.5.4F	58.0	64.9	64.8	63.2	85.4	67.7
"	1.6.3F	66.1	66.8	65.7	62.8	86.5	70.4
"	1.6.4F	52.1	--	64.7	61.7	84.5	66.9
"	4.14.1F	62.5	66.0	62.8	61.1	86.1	64.0
"	4.14.3F	55.8	59.8	60.0	58.1	84.5	63.1
"	4.14.4F	44.8	--	58.4	57.6	83.8	61.6
"	4.14.6F	60.1	64.5	61.2	59.0	84.4	62.5
"	5.15.3F	37.9	--	67.4	64.2	85.9	67.6
"	5.15.4F	50.1	68.3	69.9	66.3	89.6	71.0
"	5.15.7F	51.7	67.1	68.7	65.5	88.9	70.2
"	5.15.8F	51.7	67.0	67.4	64.5	87.1	69.2

*Over 92 ksi. Load corresponding to σ_u exceeded capacity of the machine.

TABLE 6: OBSERVED STRAINS AND OTHER MECHANICAL PROPERTIES

Matr.	Test No.	strain at strain hardening, ϵ_{st}, percent	Elongation (8 in.), percent	Reduction of Area, percent	Strain Hardening Modulus E_{st} in ksi			
					E_{st1}	E_{st2}	$E_{st3(a)}$	$E_{st3(b)}$
A	1.1.1W	0.95*	19.8	57.2	700	590*	530	546
"	1.1.2W	2.51*	18.0	59.4	406	600*	406	602
"	4.13.1W	1.80*	21.2	61.4	600	590*	574	730
"	4.13.2W	--	21.1	58.7	--	--	--	--
"	1.1.3F	2.32*	--	--	2,000	705*	852	895
"	1.1.4F	1.08*	--	--	4,200	726*	680	770
"	4.13.3F	1.20*	21.5	56.0	9,150	688*	705	550
"	4.13.4F	1.19*	--	--	1,900	670*	854	755
B	1.7.1P	1.75	20.6	54.5	540	576	513	507
"	1.7.2P	1.23	19.2	51.4	4,020	645	737	639
"	1.7.3P	1.12*	19.2	45.8	2,560	634*	850	850
"	1.9.1P	3.25	22.0	47.0	930	350	812	220
"	1.9.2P	2.29	20.0	36.4	830	775	598	500
"	1.9.3P	1.45	21.3	50.7	1,500	441	685	590
"	1.9.4P	1.21*	19.5	59.3	480	530*	480	720
"	1.11.1P	2.05	24.9	46.0	2,030	446	461	475
"	1.11.2P	2.02	21.2	40.6	6,960	557	841	493
"	1.11.3P	2.05	21.7	47.2	6,274	485	993	794
"	1.11.4P	2.09	23.4	48.7	1,375	340	960	650
B	1.2.1W	1.95	21.6	44.2	5,320	642	591	630
"	1.2.4W	1.67*	21.2	61.6	393	580*	655	900
1.	1.3.1W	1.85	21.0	49.2	2,920	505	987	890
"	1.3.2W	2.06	23.3	44.2	3,300	559	920	822
"	1.4.1W	2.18	22.6	62.3	868	496	819	859
"	1.4.3W	2.27	20.5	55.5	3,960	456	871	826
"	1.5.1W	2.55	21.5	58.3	--	--	--	--
"	1.5.2W	3.28	21.4	42.0	8,372	479	926	--
"	1.6.1W	1.91	21.2	53.2	--	--	--	411
"	1.6.2W	1.75	21.4	39.5	1,750	497	895	769
"	4.14.2W	1.66*	23.1	44.0	3,510	521*	1031	965
"	4.14.5W	1.36*	22.2	45.2	4,210	589*	950	1122
"	5.15.1W	2.52	20.7	40.5	696	619	538	569
"	5.15.2W	1.97	20.2	43.2	2,500	644	382	744
"	5.15.5W	2.12	19.0	47.0	1,425	499	979	402
"	5.15.6W	2.20	18.0	37.0	1,394	523	836	717
B	1.2.2F	1.65*	21.2	58.2	2,500	565*	975	830
"	1.2.3F	1.58*	21.2	50.5	1,050	573*	990	1,020
"	1.3.3F	1.77	36.1	58.6	1,883	550	664	--
"	1.4.2F	1.90	24.6	53.3	3,710	322	660	434
"	1.4.4F	2.62	23.1	55.0	6,840	380	1,160	402
"	1.5.3F	2.10	22.6	58.1	2,720	560	730	670
"	1.5.4F	1.90	22.5	44.0	5,030	542	355	472
"	1.6.3F	1.99	18.8	55.1	9,825	542	805	941
"	1.6.4F	1.70	18.1	57.5	7,960	516	820	452
"	4.14.1F	1.18*	22.7	55.5	2,240	630*	833	807
"	4.14.3F	1.05*	23.4	53.2	1,835	643*	932	870
"	4.14.4F	1.08*	23.9	52.4	2,380	648*	960	961
"	4.14.6F	1.19*	23.6	53.8	2,400	618*	835	825
"	5.15.3F	2.00	21.0	52.6	1,660	490	903	--
"	5.15.4F	2.00	20.5	57.3	4,250	575	727	638
"	5.15.7F	2.13	18.0	53.0	1,245	484	736	955
"	5.15.8F	2.01	20.0	45.0	1,374	522	764	900

*Value based on dial gage readings

TABLE 7: SUMMARY OF STRESS (All Values in ksi)

Material	Origin	Value of	Proportional Limit σ_p	Upper Yield σ_{uy}	Dynamic Yield σ_{yd}	Static Yield σ_{ys}	Ultimate Strength σ_u	Fracture Stress σ_f
A	Web	Average	45.9	65.0	63.8	61.4	87.0	69.9
"	"	Median	47.9	64.6	64.1	61.1	87.1	67.3
"	Flange	Average	49.3	68.1	65.5	63.5	89.6	68.6
"	"	Median	50.1	69.2	65.3	63.4	89.6	68.6
"	All	Average	47.6	66.5	64.7	62.4	87.5	69.6
"	"	Median	47.9	65.3	64.5	62.4	87.4	67.4
B	Plate	Average	63.2	67.9	64.8	62.2	86.3	68.0
"	"	Median	65.6	67.3	63.9	62.1	86.7	67.9
"	Web	Average	61.9	66.8	64.8	62.1	84.9	68.8
"	"	Median	62.5	68.0	65.4	62.9	85.5	70.5
"	Flange	Average	52.9	65.5	64.2	61.9	85.6	66.4
"	"	Median	52.5	66.0	64.7	62.2	85.4	66.9
"	All	Average	58.7	66.8	64.6	62.0	85.5	67.7
"	"	Median	61.4	66.8	64.7	62.3	86.2	67.8
A&B	Plate	Average	63.2	67.9	64.8	62.2	86.3	68.0
"	"	Median	65.6	67.3	63.9	62.1	86.7	67.9
"	Web	Average	58.7	66.5	64.6	61.9	85.3	69.0
"	"	Median	61.4	66.4	65.0	61.9	86.4	69.4
"	Flange	Average	52.2	66.1	64.5	62.2	85.8	66.5
"	"	Median	52.5	66.4	64.8	62.8	85.6	67.0
"	All	Average	57.0	66.7	64.6	62.1	85.7	67.9
"	"	Median	58.5	66.5	64.7	62.3	86.4	67.7
"	"	Standard Deviation	9.9	2.6	2.6	2.3	2.2	3.4
"	"	Coefficient of Variation%	17.3	3.9	4.1	3.7	2.6	5.0

TABLE 8: SUMMARY OF STRAIN AND OTHER MECHANICAL PROPERTIES

Mat'l	Origin	Value of	Strain at Strain-Hardening ϵ_{st}(%)	Percent Elongation	Percent Reduction of Area	E_{st1} ksi	E_{st2} ksi	$E_{st3(a)}$ ksi	$E_{st3(b)}$ ksi
A	Web	Average	1.75	20.0	59.2	569	593	503	626
"	"	Median	1.80	20.4	59.0	600	590	530	602
"	Flange	Average	1.45	21.5	56.0	4312	697	773	742
"	"	Median	1.20	21.5	56.0	3100	696	778	762
"	All	Average	1.58	20.3	58.5	2708	653	657	692
"	"	Median	1.20	21.1	58.7	1900	670	680	730
B	Plate	Average	1.86	21.2	48.0	2500	525	721	585
"	"	Median	2.02	21.2	47.2	1500	530	737	590
"	Web	Average	2.08	21.2	47.9	2901	543	813	759
"	"	Median	2.02	21.3	44.7	2710	522	883	795
"	Flange	Average	1.76	22.4	53.7	3465	538	815	745
"	"	Median	1.90	22.5	53.8	2400	550	820	825
"	All	Average	1.90	21.7	50.2	3024	537	789	706
"	"	Median	1.96	21.3	51.0	2390	542	826	732
A&B	Plate	Average	1.86	21.2	48.0	2500	525	721	585
"	"	Median	2.02	21.2	47.2	1500	530	737	590
"	Web	Average	2.03	20.9	50.2	2490	552	758	735
"	"	Median	1.97	21.2	48.1	1750	559	836	744
"	Flange	Average	1.70	22.4	53.8	3626	569	807	745
"	"	Median	1.77	22.0	54.4	2400	565	820	807
"	All	Average	1.86	21.5	51.0	2979	553	771	704
"	"	Median	1.91	21.2	52.6	2240	559	819	730
"	"	Standard Deviation	0.52	2.7	6.8	2400	95	186	197
"	"	Coefficient of Variation%	27.9	12.5	13.4	81	17	24	28

TABLE 9: AVERAGE VALUES OF GROUPS OF SPECIMENS

Group	No. of Specimens	σ_{yd} ksi	σ_{ys} ksi	σ_u ksi	ϵ_{st} %	E_{st2} ksi	E_{st3}* ksi
Plate Specimens	11	64.8	62.2	86.3	1.86	525	656
Web Specimens	20	64.6	61.9	85.3	2.02	530	663
Flange Specimens	21	64.5	62.2	85.8	1.70	569	776
Specimens with yield lines	5	63.8	61.2	84.8	1.92	526	726
Specimens without yield lines**	5	63.6	61.7	84.6	1.89	518	723
Specimens with thickness							
from 0.201 to 0.300 in.	12	66.8	63.4	85.8	2.21	509	692
from 0.301 to 0.400 in.	16	64.9	62.4	85.3	1.93	536	797
from 0.401 to 0.500 in.	6	62.5	60.3	84.8	2.12	466	605
from 0.501 to 0.600 in.	10	63.9	61.8	86.8	1.60	591	704
from 0.601 to 0.700 in.	4	60.6	58.9	84.7	1.12	635	878
from 0.701 to 0.800 in.	--	--	--	--	--	--	--
from 0.801 to 0.900 in.	4	65.5	63.5	89.6	1.45	697	758
Specimens from shapes of weight							
from 11 to 20 lbs.	8	68.1	65.0	87.7	2.12	544	718
from 21 to 30 lbs.	8	64.9	62.0	84.6	2.15	523	687
from 31 to 40 lbs.	11	63.8	61.6	84.9	1.95	512	803
from 41 to 50 lbs.	--	--	--	--	--	--	--
from 51 to 60 lbs.	6	60.3	58.6	83.5	1.25	608	924
from 61 to 70 lbs.	--	--	--	--	--	--	--
from 71 to 80 lbs.	4	64.8	62.4	87.7	1.40	649	695
from 81 to 90 lbs.	4	64.5	62.5	87.1	1.71	655	660
All Specimens	52	64.6	62.1	85.7	1.86	553	737

* The value of E_{st3} is the average of $E_{st3(a)}$ and $E_{st3(b)}$.

** These include only the specimens from the same heat, shape and origin as the corresponding specimens from the group with yield lines.

TABLE 10: RATIO σ_{yd}/σ_{ys}

Strain rate $\dot{\epsilon}$ = 44 microin./in./sec. average of 17 observations
(crosshead speed = 0.025 in./min.)

Material	Test No.	σ_{yd}/σ_{ys}	Material	Test No.	σ_{yd}/σ_{ys}
A	1.1.1W	1.023	B	1.5.2W	1.090
"	1.1.2W	1.042	"	1.6.1W	1.050
"	4.13.1W	1.035	"	1.6.2W	1.051
"	4.13.2W	1.054	"	4.14.2W	1.032
"	1.1.3F	1.035	"	4.14.5W	1.032
"	1.1.4F	1.027	"	5.15.1W	1.051
"	4.13.3F	1.032	"	5.15.2W	1.064
"	4.13.4F	1.034	B	5.15.5W	1.038
B	1.7.1P	1.013	"	5.15.6W	1.036
"	1.7.2P	1.033	"	1.2.2F	1.033
"	1.7.3P	1.034	"	1.2.3F	1.026
"	1.9.1P	1.033	"	1.3.3F	1.043
"	1.9.2P	1.042	"	1.4.2F	1.053
"	1.9.3P	1.040	"	1.4.4F	1.027
"	1.9.4P	1.028	"	1.5.3F	1.032
"	1.11.1P	1.047	"	1.5.4F	1.025
"	1.11.2P	1.062	"	1.6.3F	1.046
"	1.11.3P	1.029	"	1.6.4F	1.048
"	1.11.4P	1.072	"	4.14.1F	1.027
"	1.2.1W	1.049	"	4.14.3F	1.033
"	1.2.4W	1.028	"	4.14.4F	1.031
"	1.3.1W	1.030	"	4.14.6F	1.037
"	1.3.2W	1.033	"	5.15.3F	1.050
"	1.4.1W	1.030	"	5.15.4F	1.054
"	1.4.3W	1.043	"	5.15.7F	1.050
"	1.5.1W	1.045	"	5.15.8F	1.047
			Average of all tests		1.040

TABLE 11: SIMULATED MILL TESTS AND MILL DATA
8 in. gage specimen used throughout

SIMULATED MILL TESTS:

Material	Test No.	Origin	Shape	σ_{ym}, ksi	σ_u, ksi	Percent Elongation
A	4.13.5F	Flange	16W71	66.1	91.0	20.6
"	4.13.6F	"	"	69.7	87.4	22.9
B	5.15.9F	Flange	12B19	69.6	89.2	20.7
"	5.15.10W	Web	"	71.8	89.2	18.6
Average of the four tests				69.3	89.2	20.7

None of the specimens showed any yield lines.

MILL DATA:

Material	Origin	Shape	σ_{ym}, ksi	σ_u, ksi	Percent Elongation
A	web	16W88	71.1	91.4	19.0
"		16W71	73.0	95.6	17.0
Average for material A (2 specimens)			72.0	93.5	18.0
B	1/2" plate		66.9	86.9	19.0
"	3/8" plate		65.0	90.0	21.0
"	1/4" plate		71.8	92.2	19.0
"	Web	12B19	71.8	94.8	17.0
"	"	16B26	70.5	93.7	16.9
"	"	10W39	71.5	90.3	19.8
"	"	10W54	72.9	97.5	16.1
Average for material B (7 specimens)			70.1	92.2	18.4
Average for All (9 specimens)			70.5	92.5	18.3

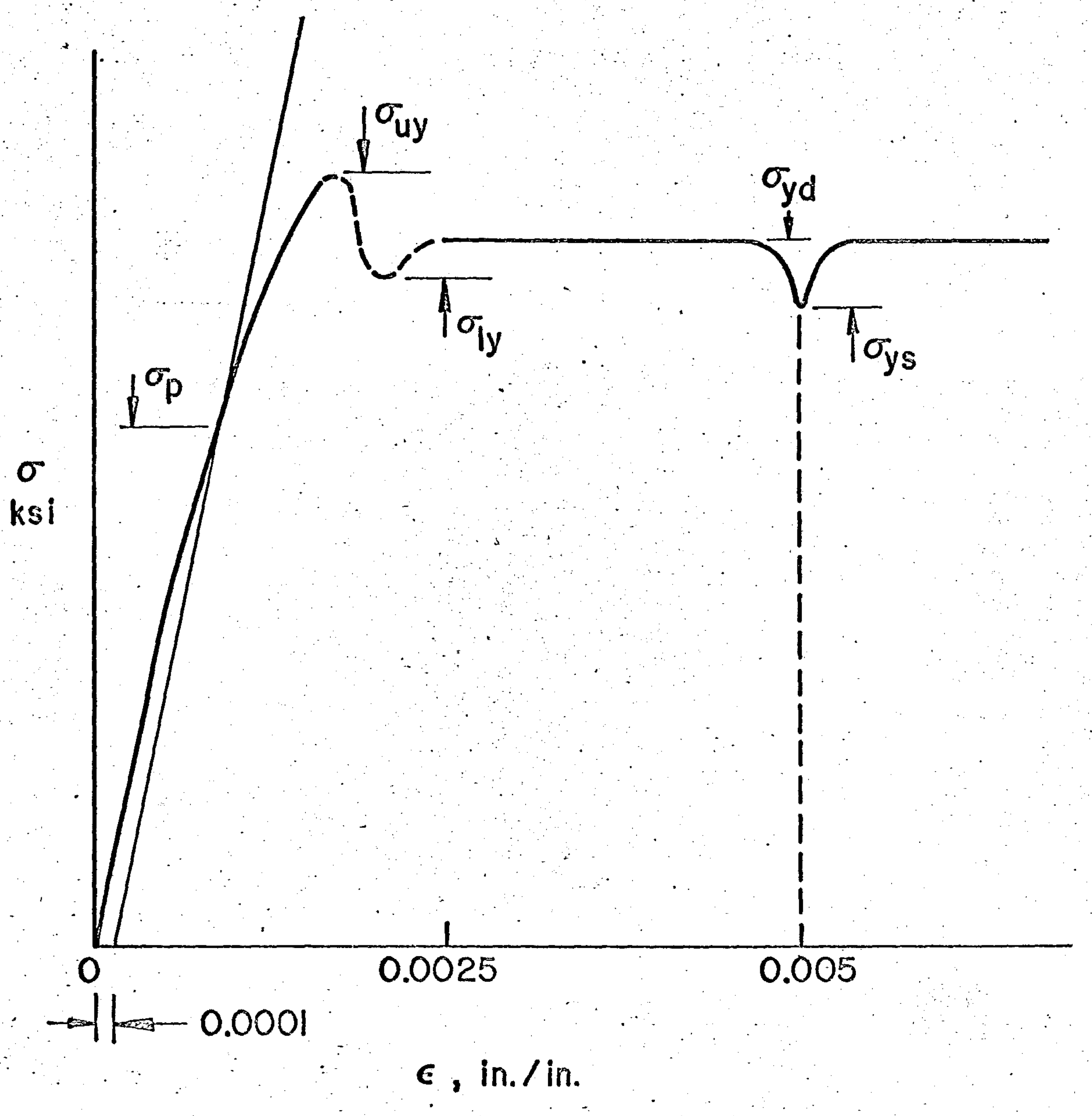


FIG. 1 SKETCH DEFINING σ_p, σ_{uy}, $\sigma_{\ell y}$, σ_{yd} and σ_{ys}

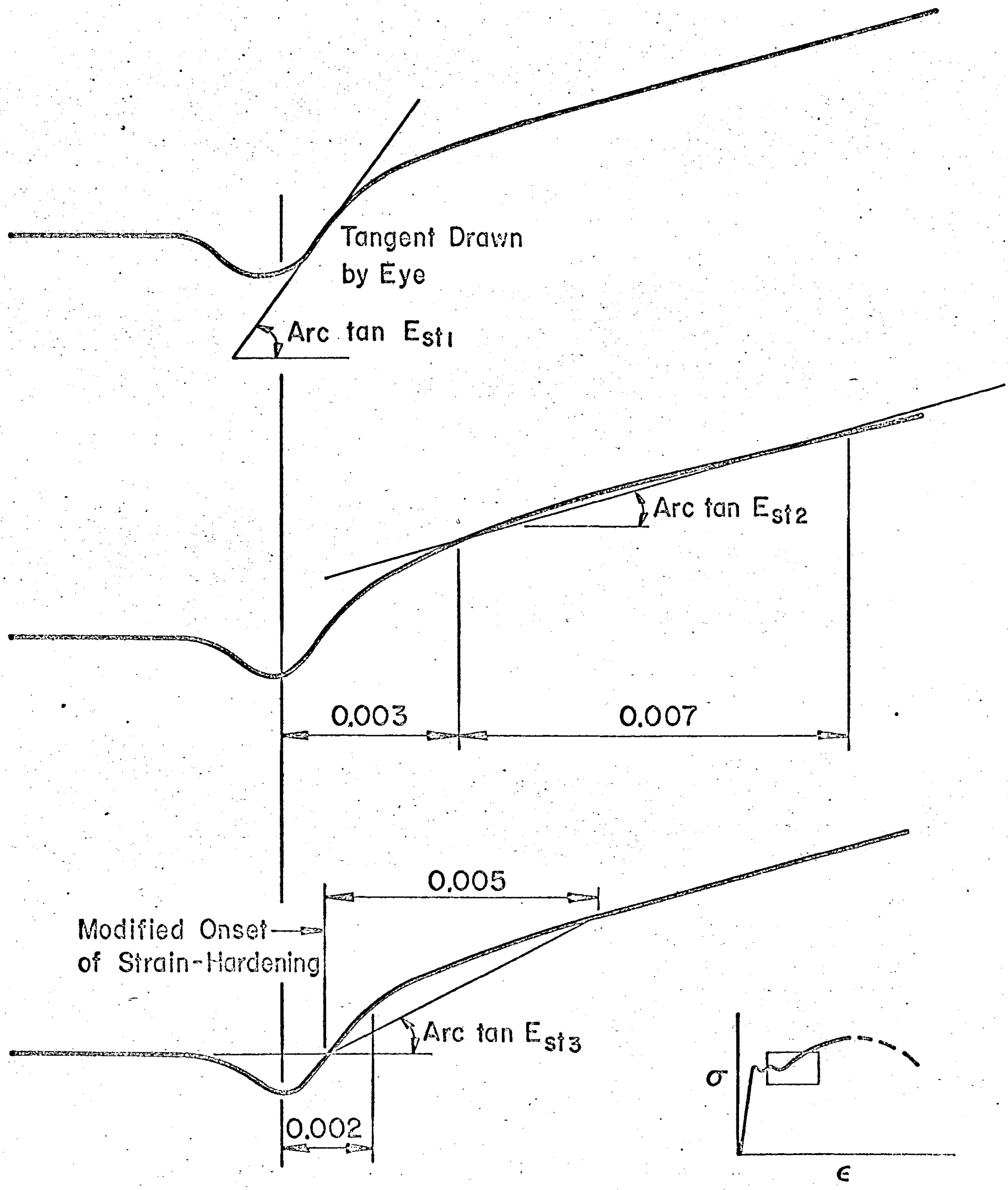


FIG. 2 SKETCH DEFINING E_{st1}, E_{st2} and E_{st3}

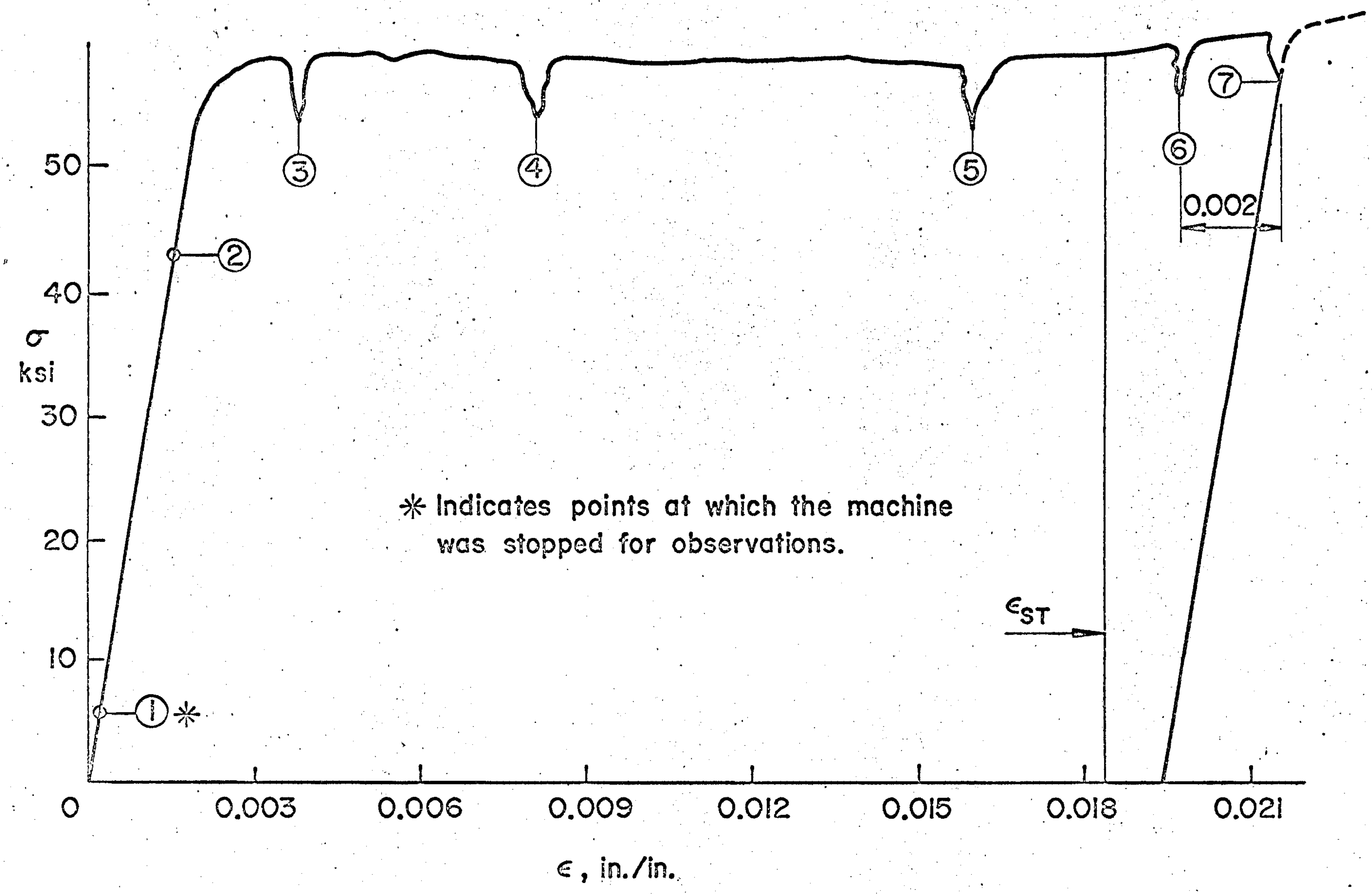


FIG. 3 SKETCH DEFINING $E_{stl(b)}$ [4]

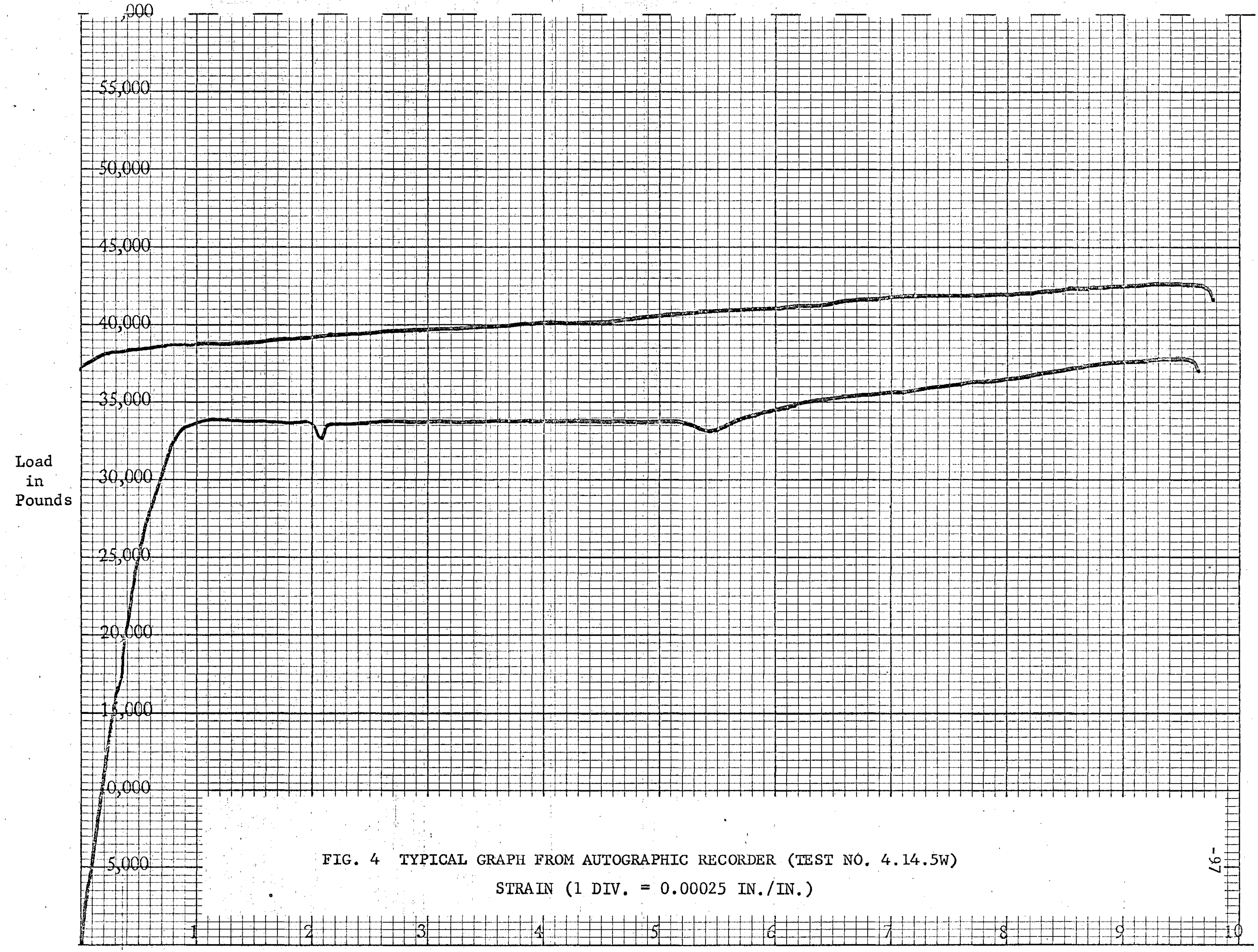


FIG. 4 TYPICAL GRAPH FROM AUTOGRAPHIC RECORDER (TEST NO. 4.14.5W)

STRAIN (1 DIV. = 0.00025 IN./IN.)

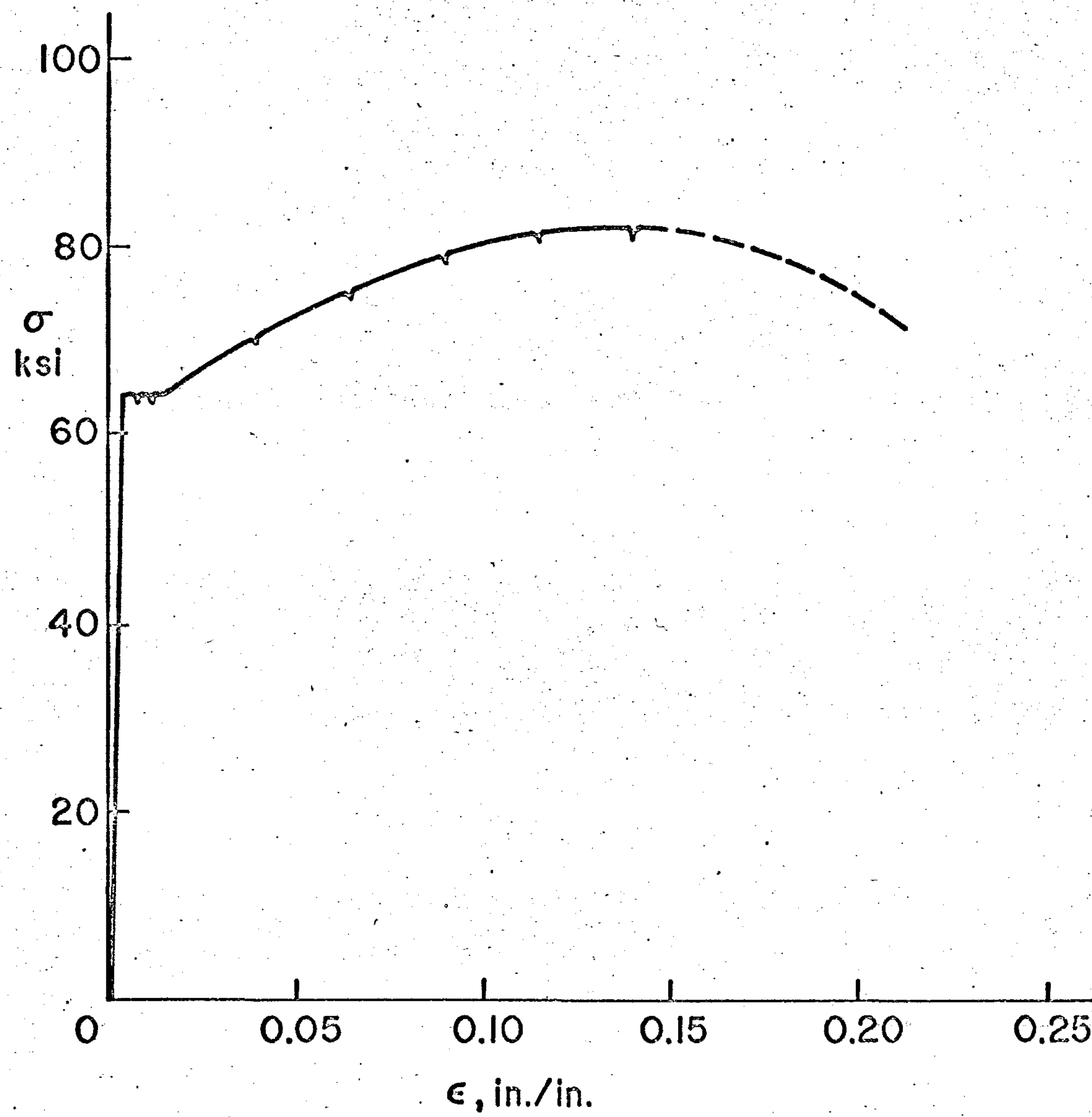


FIG. 5 TYPICAL COMPLETE STRESS-STRAIN CURVE FOR A572 (GRADE 65) STEEL (TEST NO. 1.6.2W)

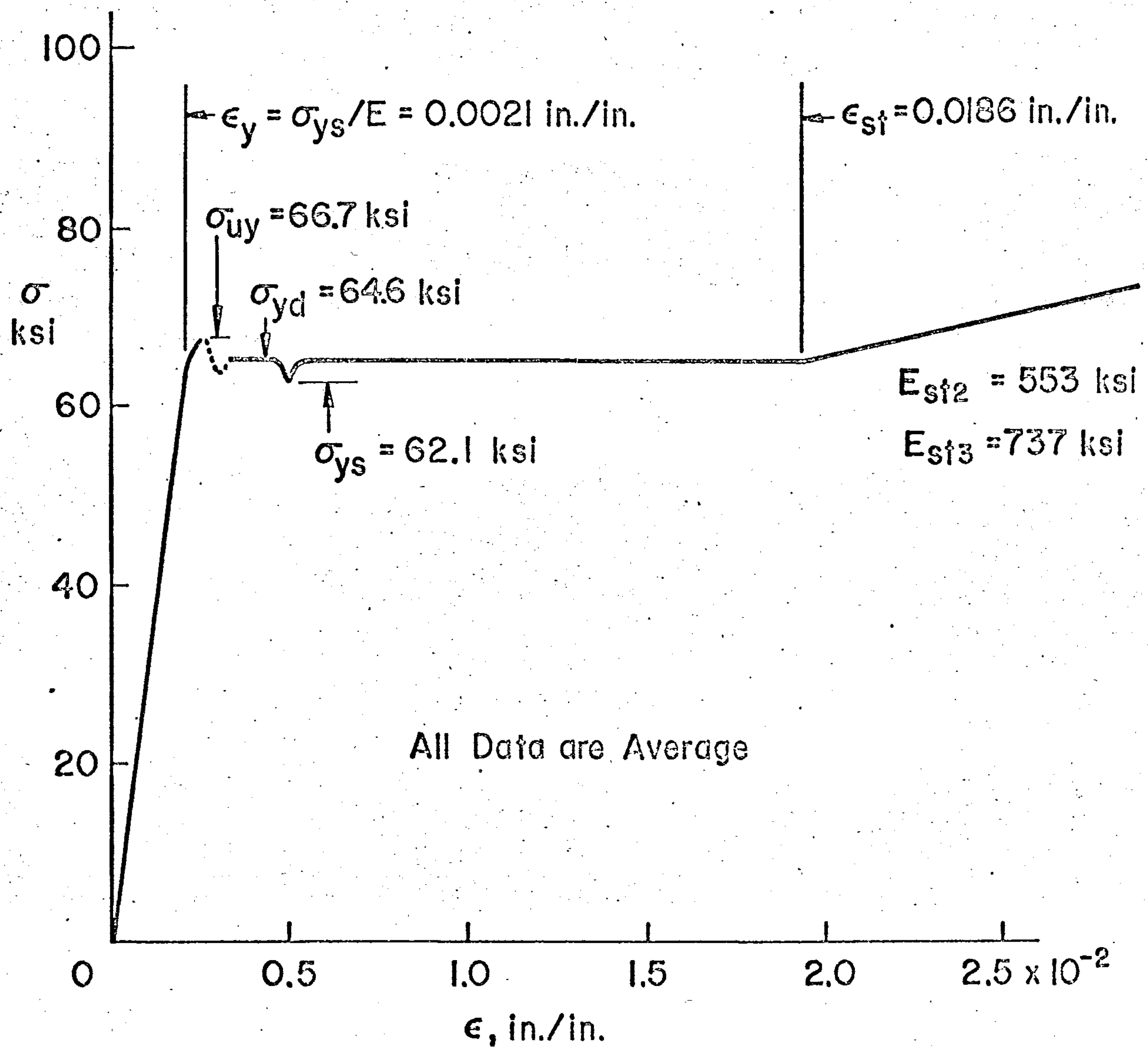


FIG. 6 IDEALIZED STRESS-STRAIN CURVE FOR A572 (GRADE 65) STEEL (WITH STRAIN-HARDENING)

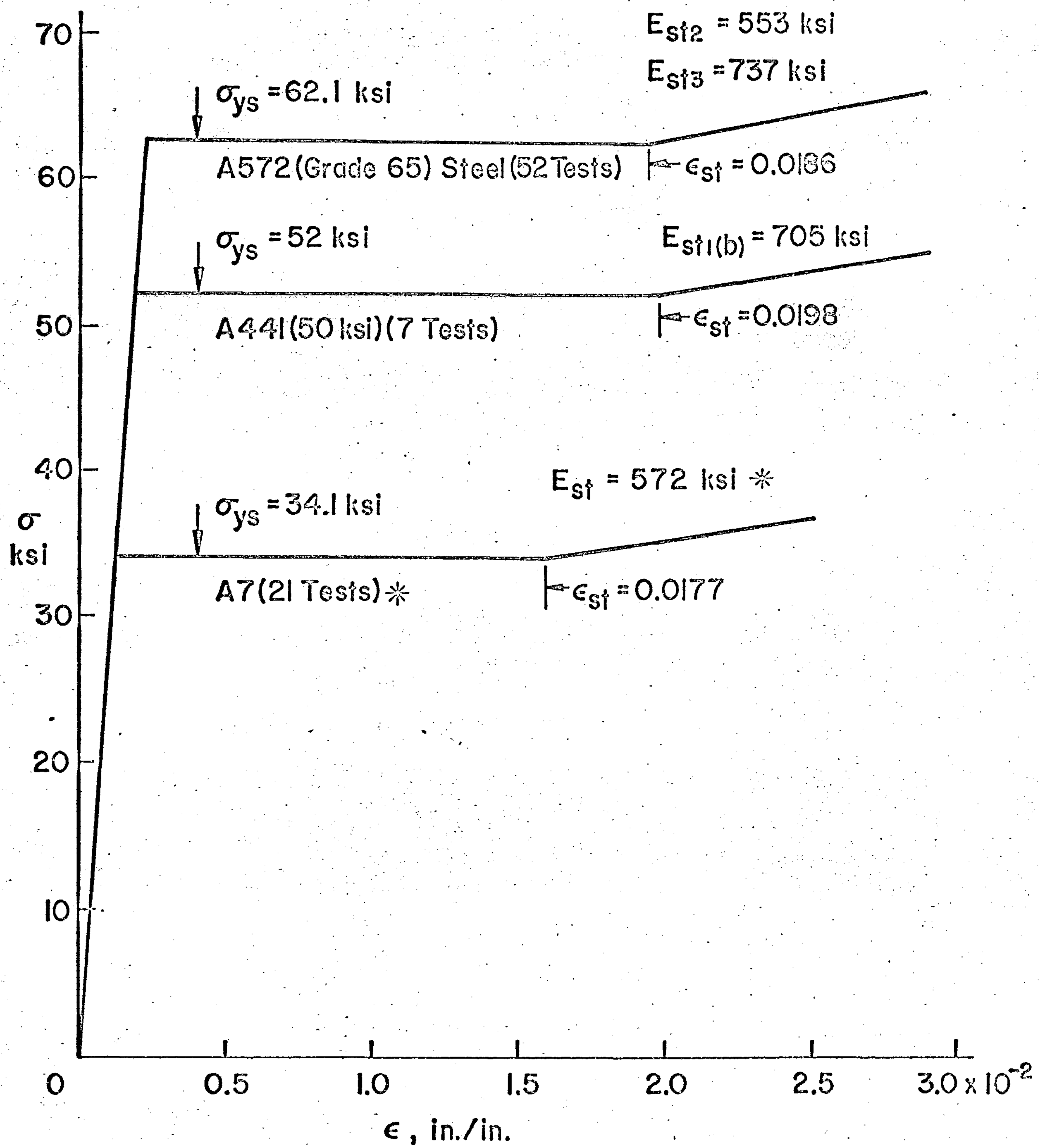


FIG. 7 IDEALIZED STRESS-STRAIN CURVES FOR A7, A441, and A572 (GRADE 65) STEELS

* Values for A7 steel taken from unpublished results of tension tests for Project 205B, 205E and 220A at Fritz Lab. Values of E_{st} are read as chords in the linear portion of the curve and lie somewhere between E_{st3} and E_{st2}.

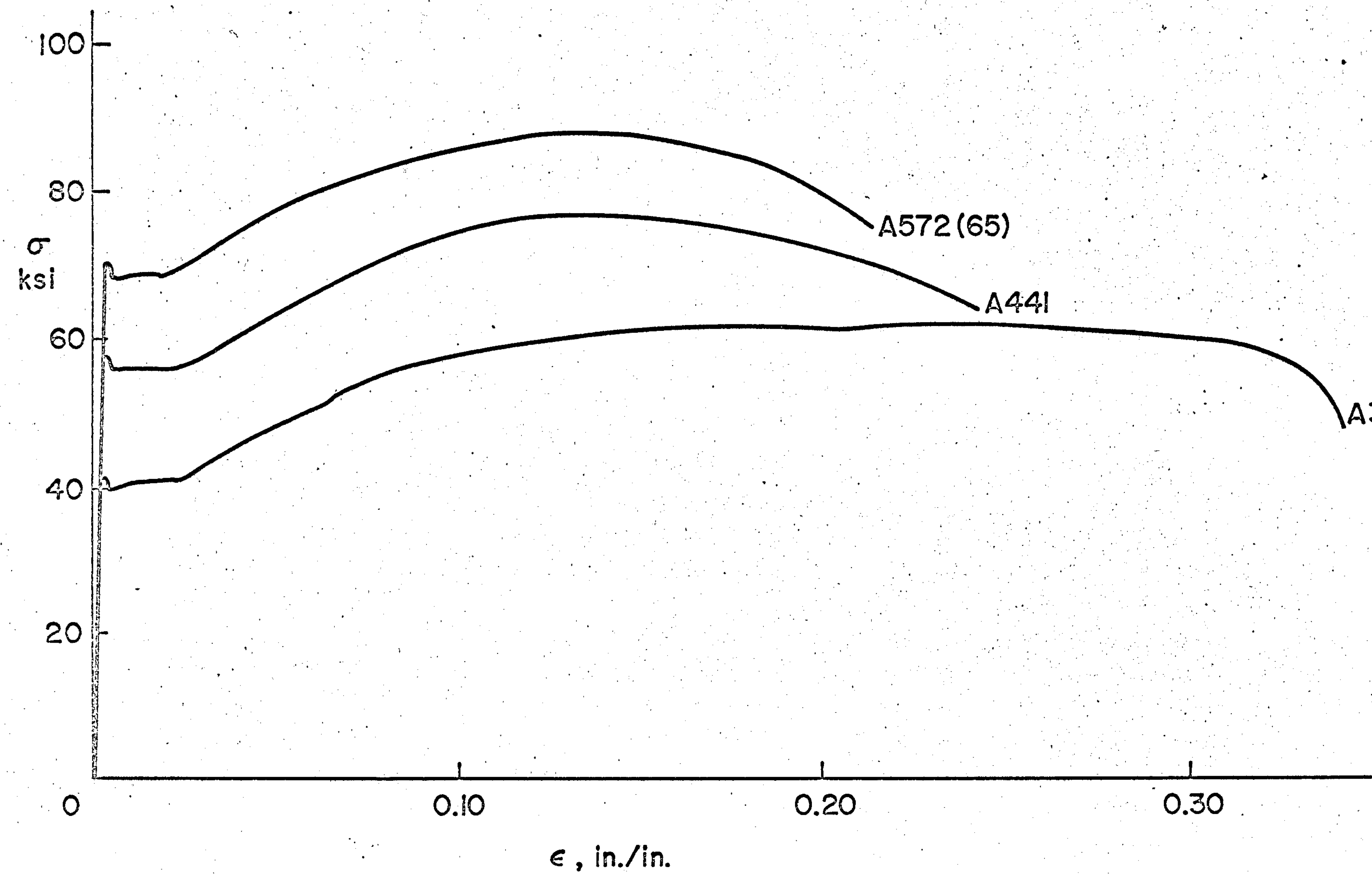


FIG. 8 TYPICAL COMPLETE STRESS-STRAIN CURVES FOR A36, A441 and A572 (GRADE 65) STEELS

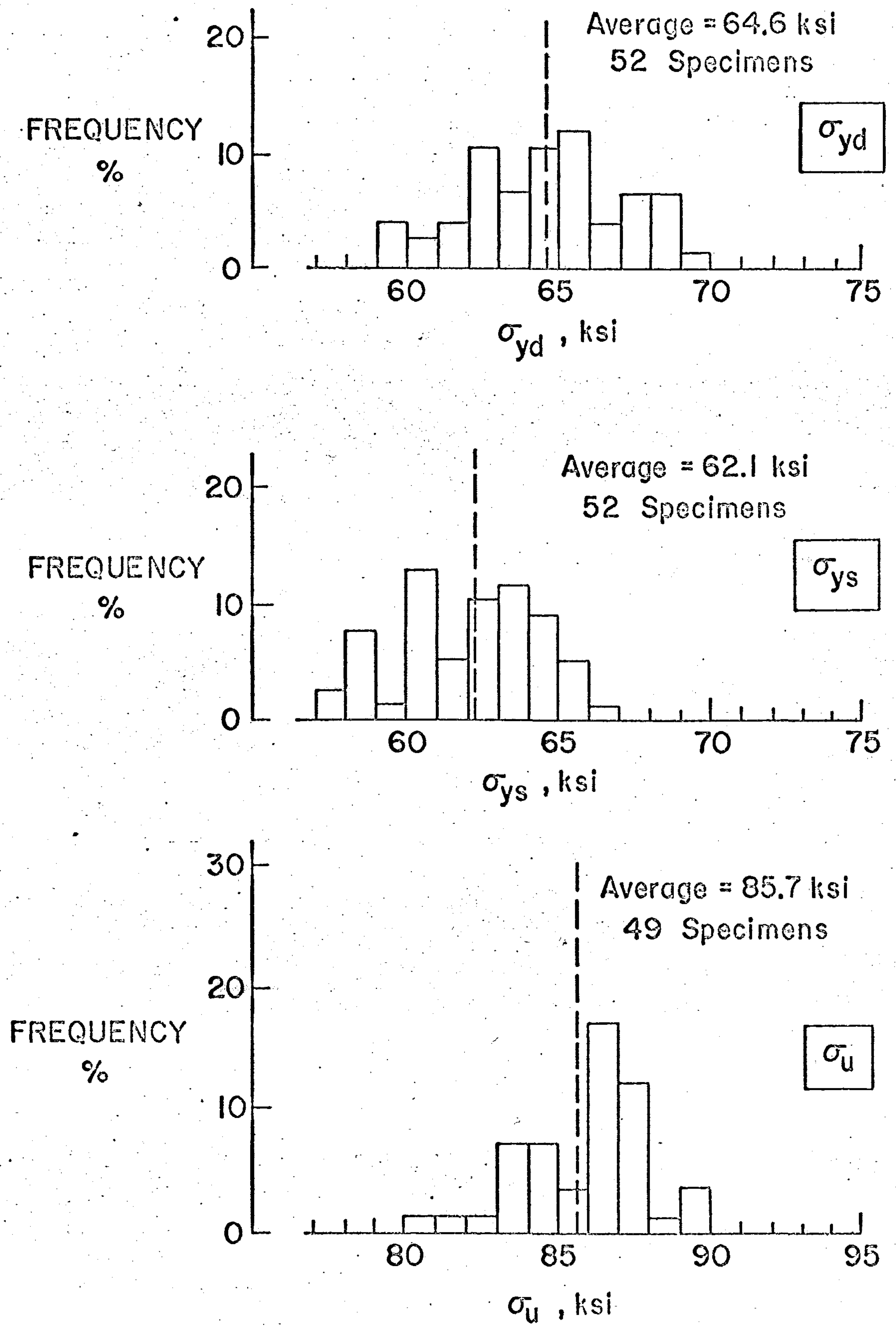
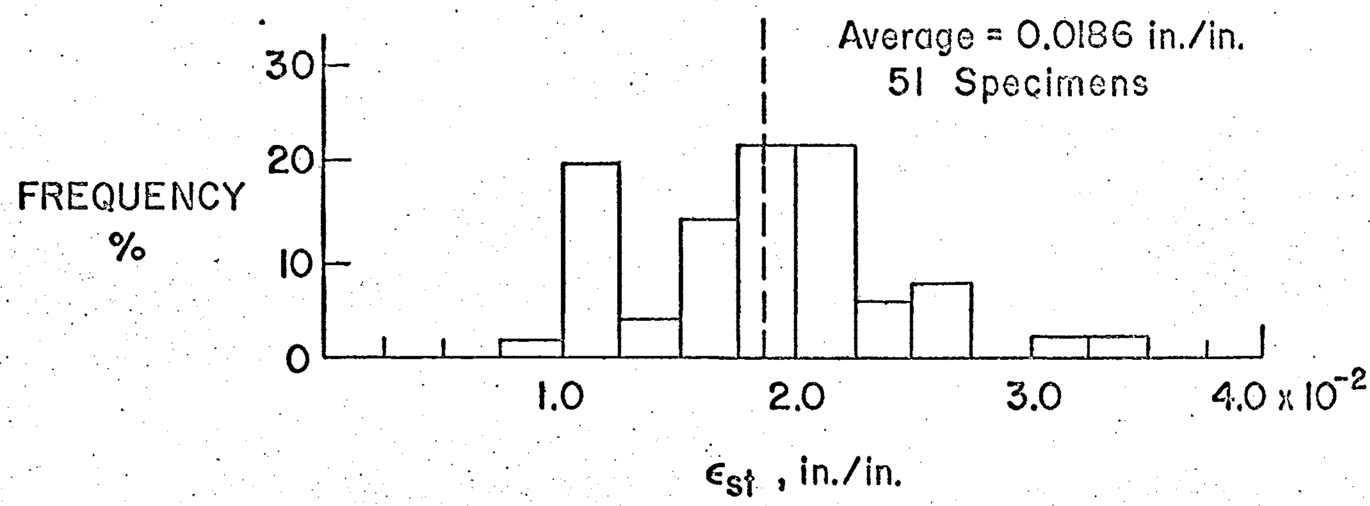
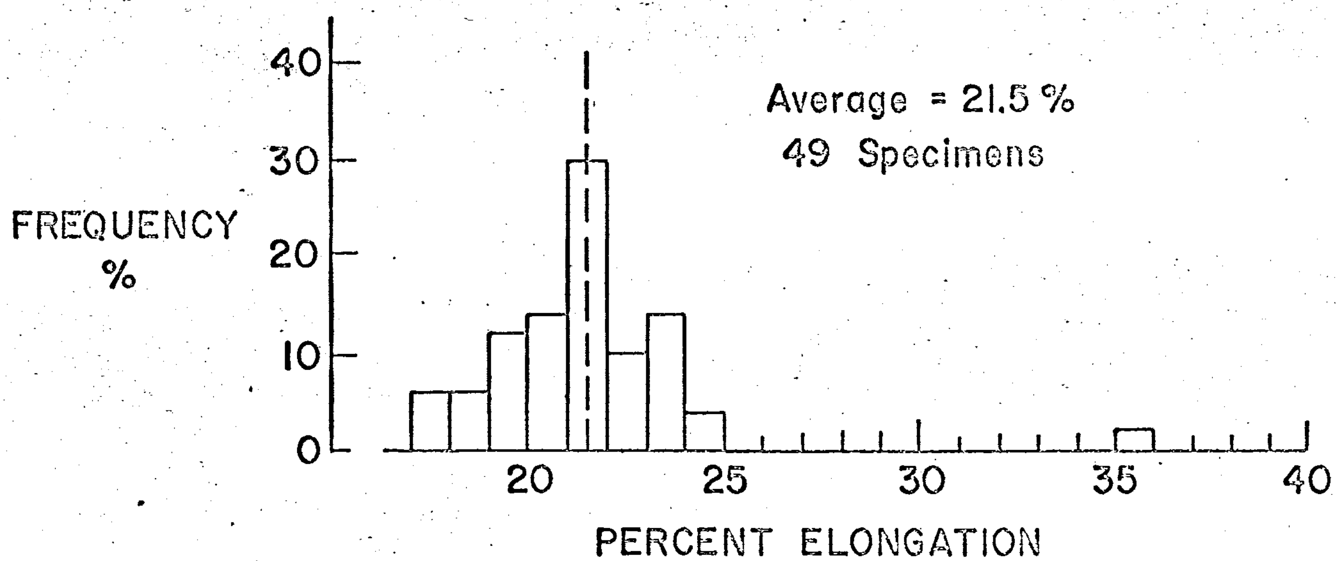


FIG. 9 HISTOGRAMS FOR σ_{yd}, σ_{ys} and σ_u





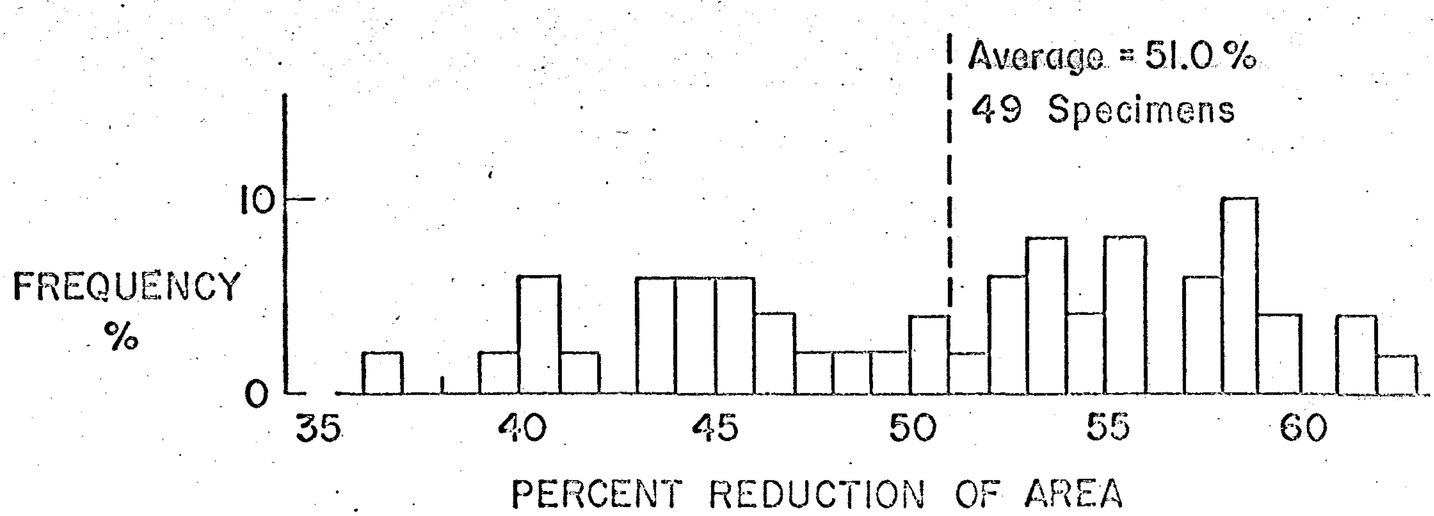


FIG. 10 HISTOGRAMS FOR ϵ_{st}, PERCENT ELONGATION AND PERCENT REDUCTION OF AREA

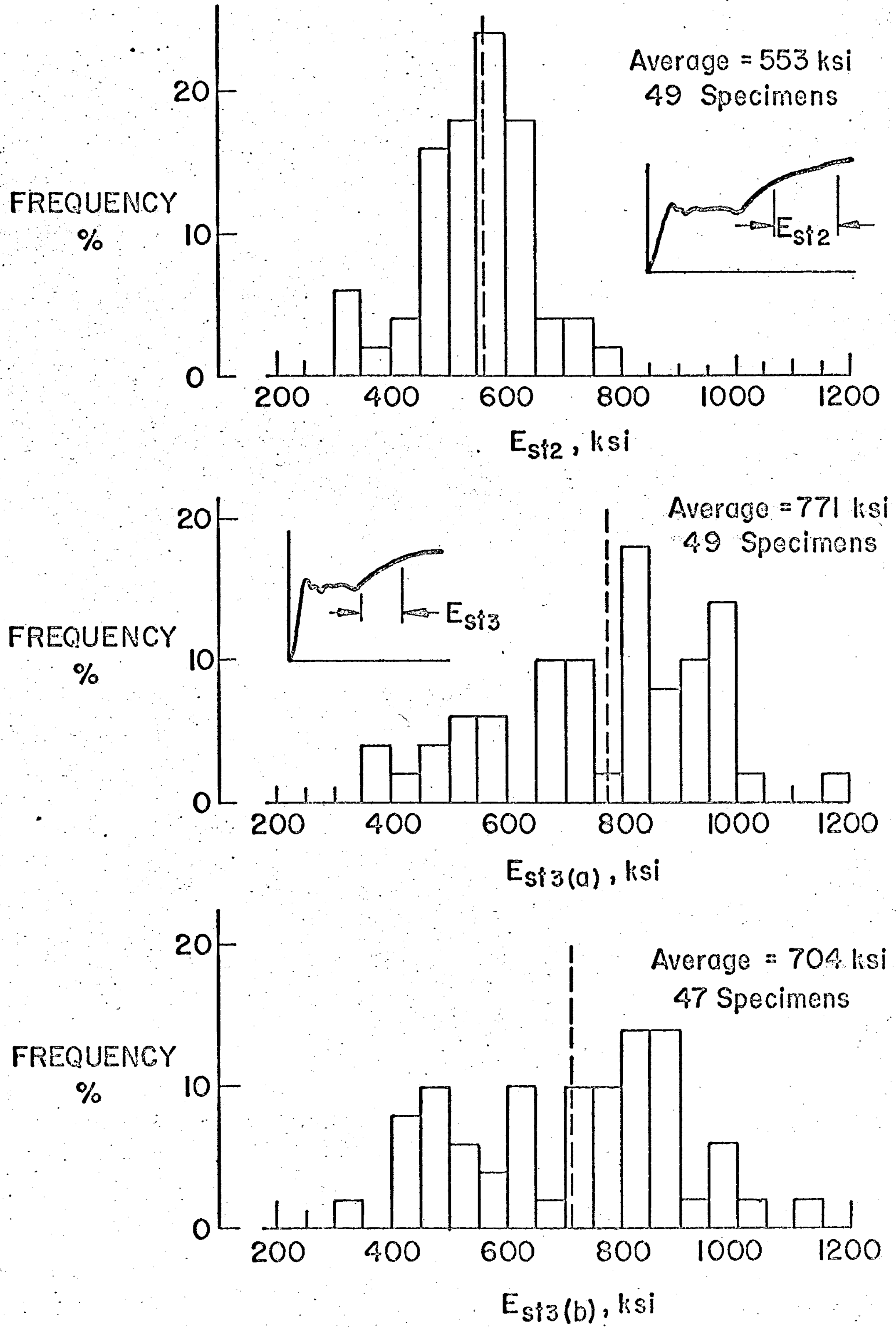


FIG. 11 HISTOGRAMS FOR E_{st2}, $E_{st3(a)}$ and $E_{st3(b)}$

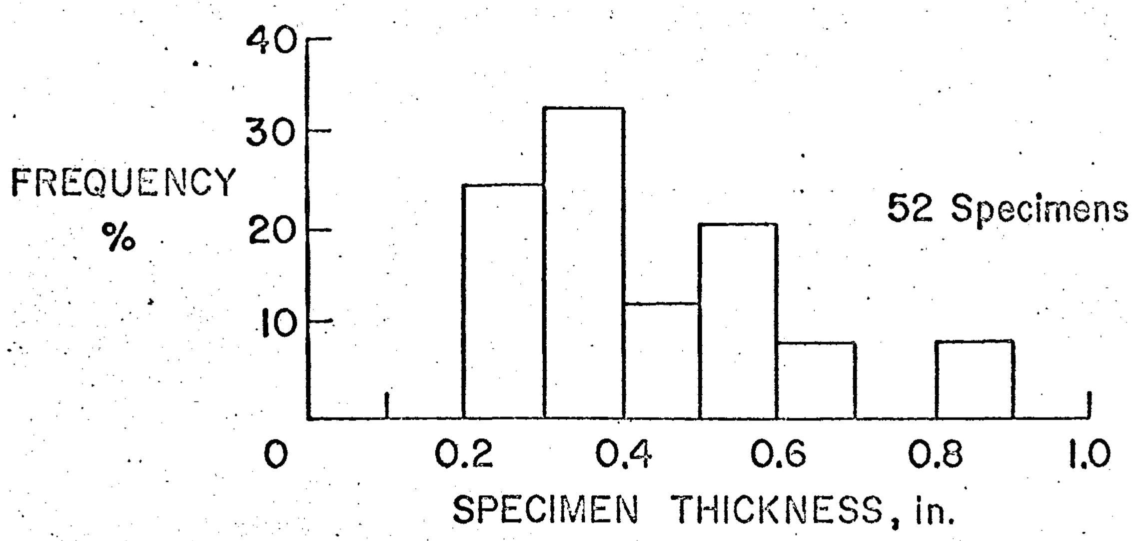


FIG. 12 HISTOGRAM FOR SPECIMEN THICKNESS

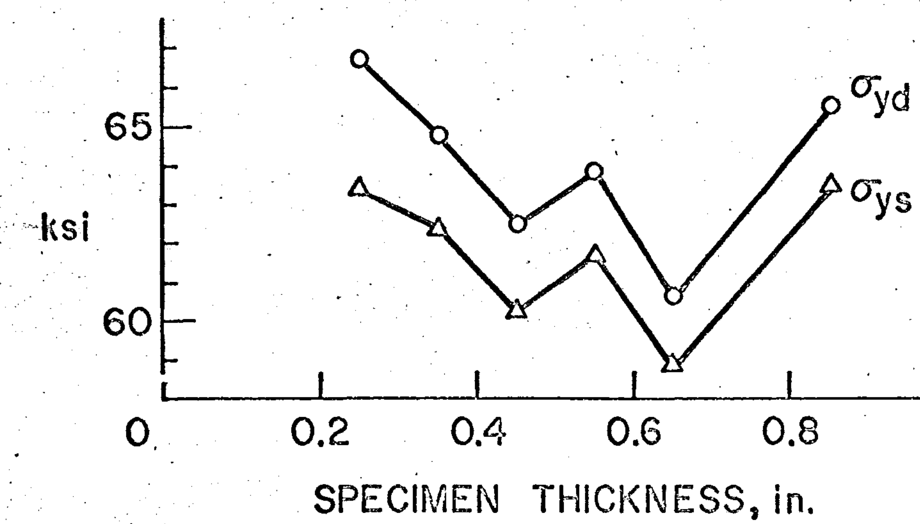


FIG. 13 VARIATION OF σ_{yd} and σ_{ys} WITH THICKNESS

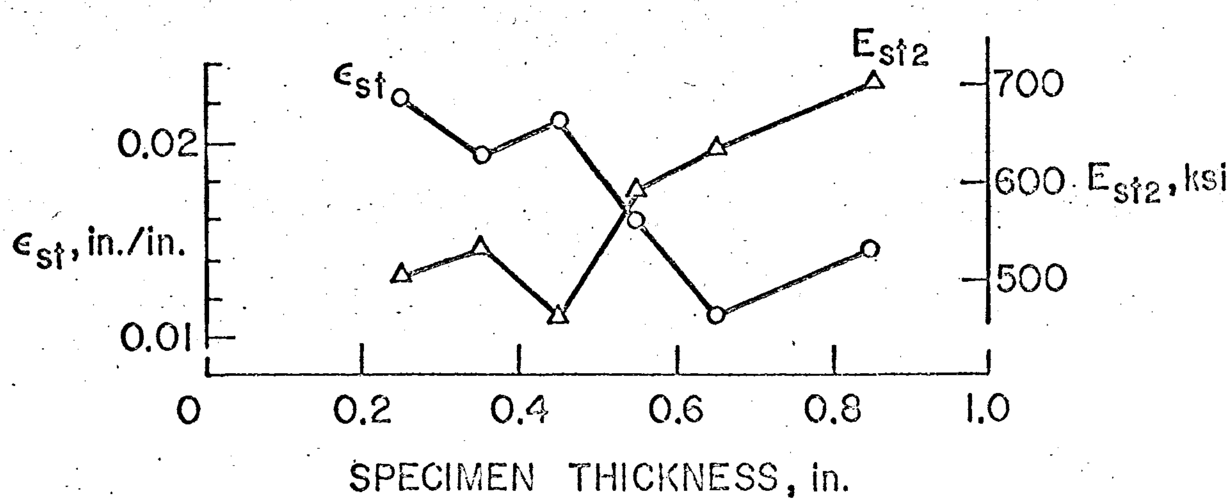


FIG. 14 VARIATION OF ϵ_{st} and E_{st2} WITH THICKNESS

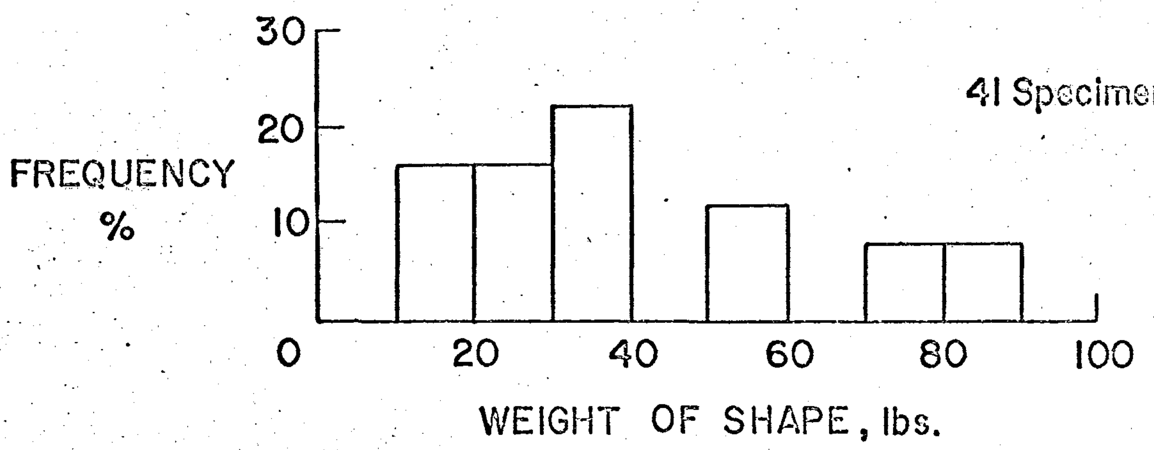


FIG. 15 HISTOGRAM FOR WEIGHT OF SHAPE

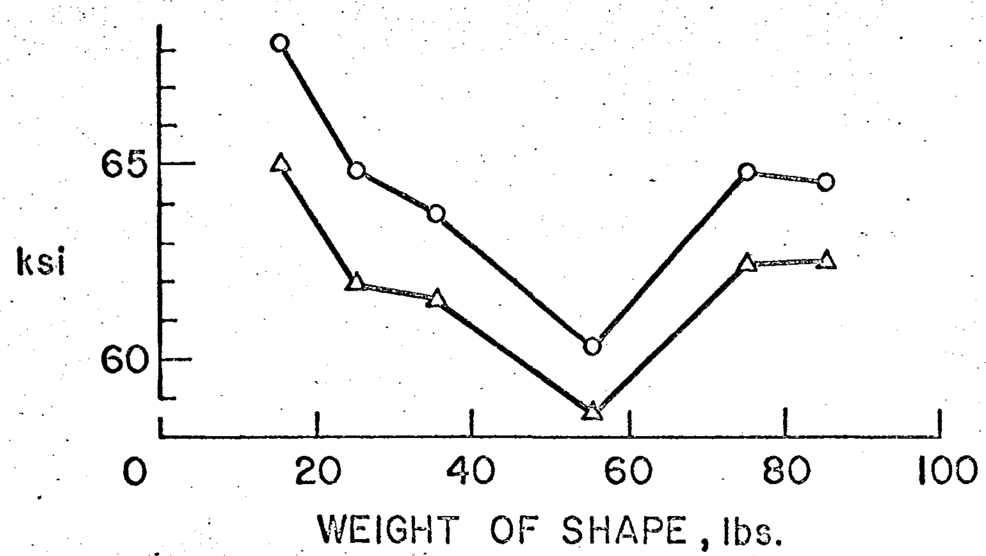


FIG. 16 VARIATION OF σ_{yd} and σ_{ys} WITH WEIGHT OF SHAPE

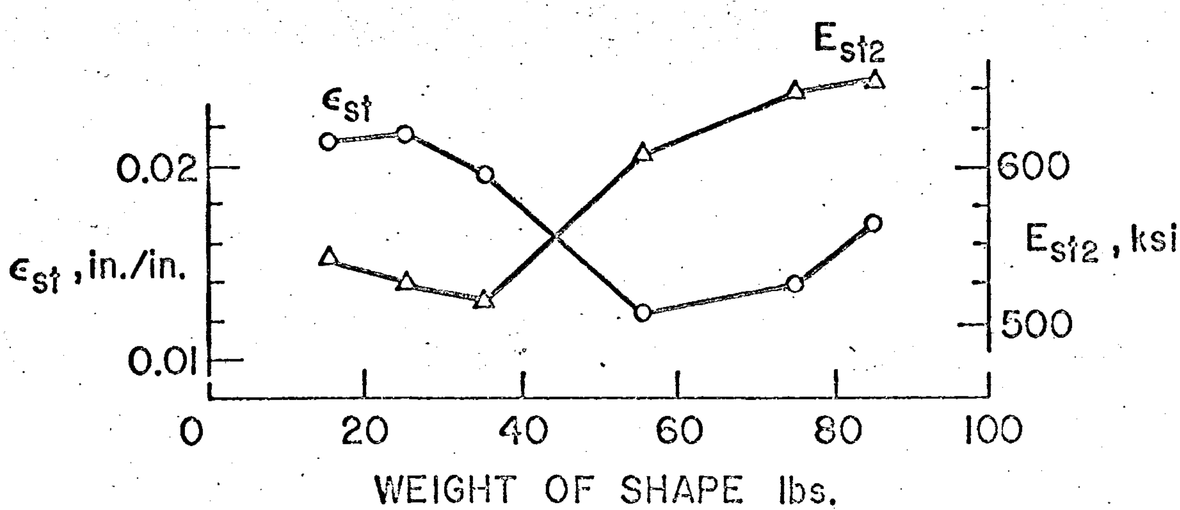


FIG. 17 VARIATION OF ϵ_{st} and E_{st2} WITH WEIGHT OF SHAPE

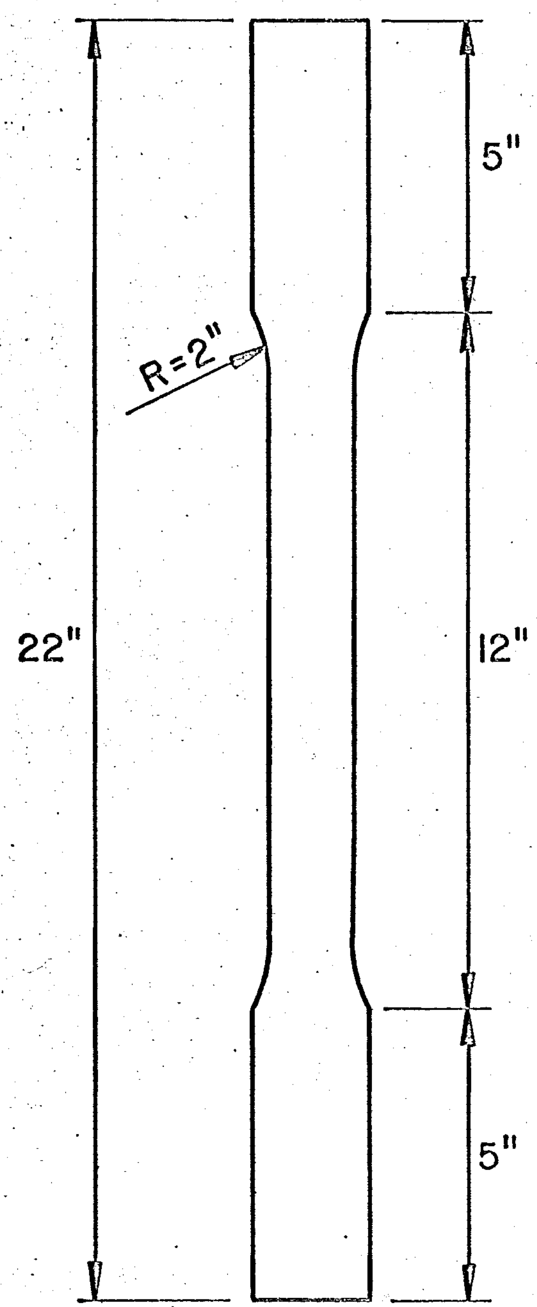


FIG. 18 SHAPE OF THE SPECIMEN

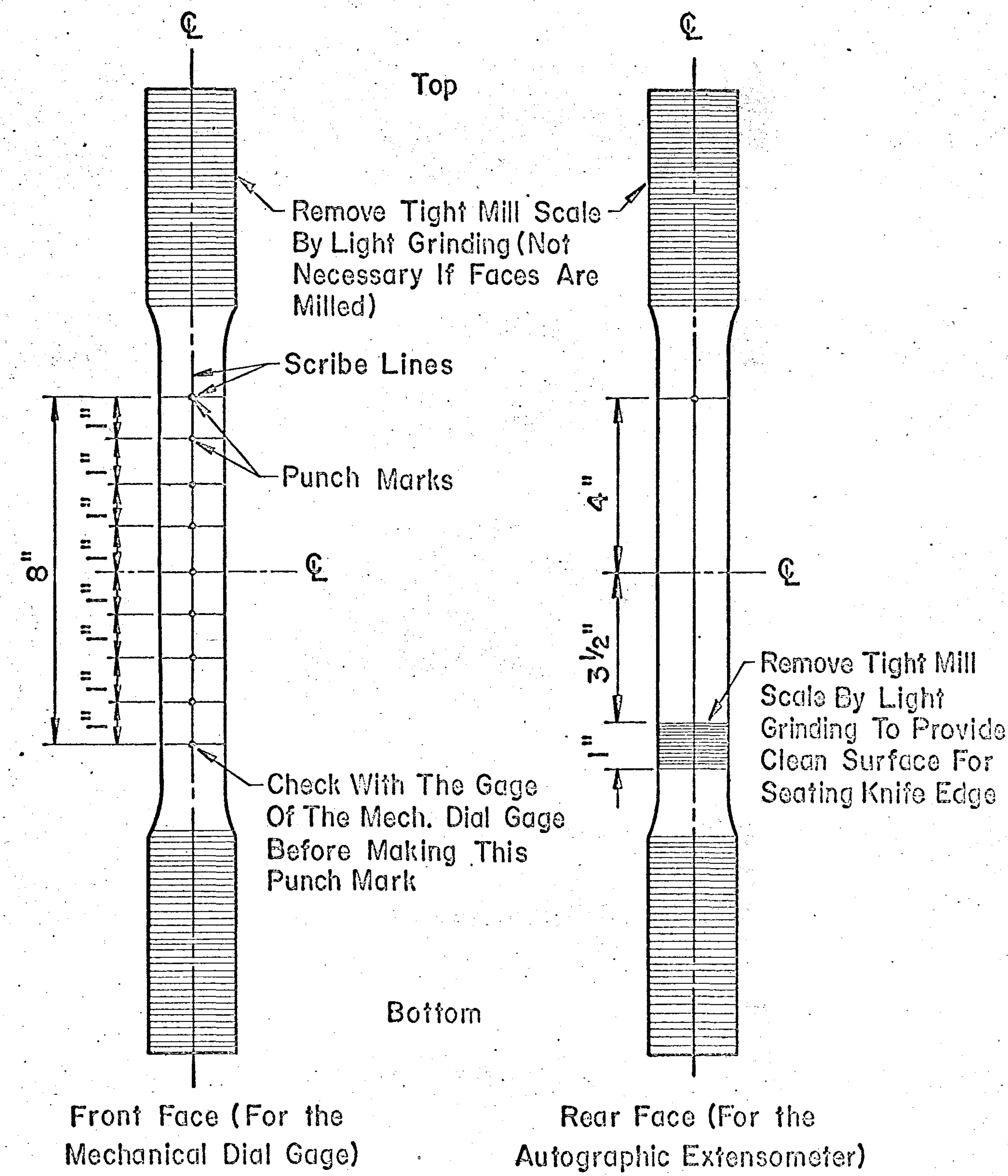


FIG. 19 SCRIBE AND PUNCH MARKS ON THE FACES OF THE SPECIMEN

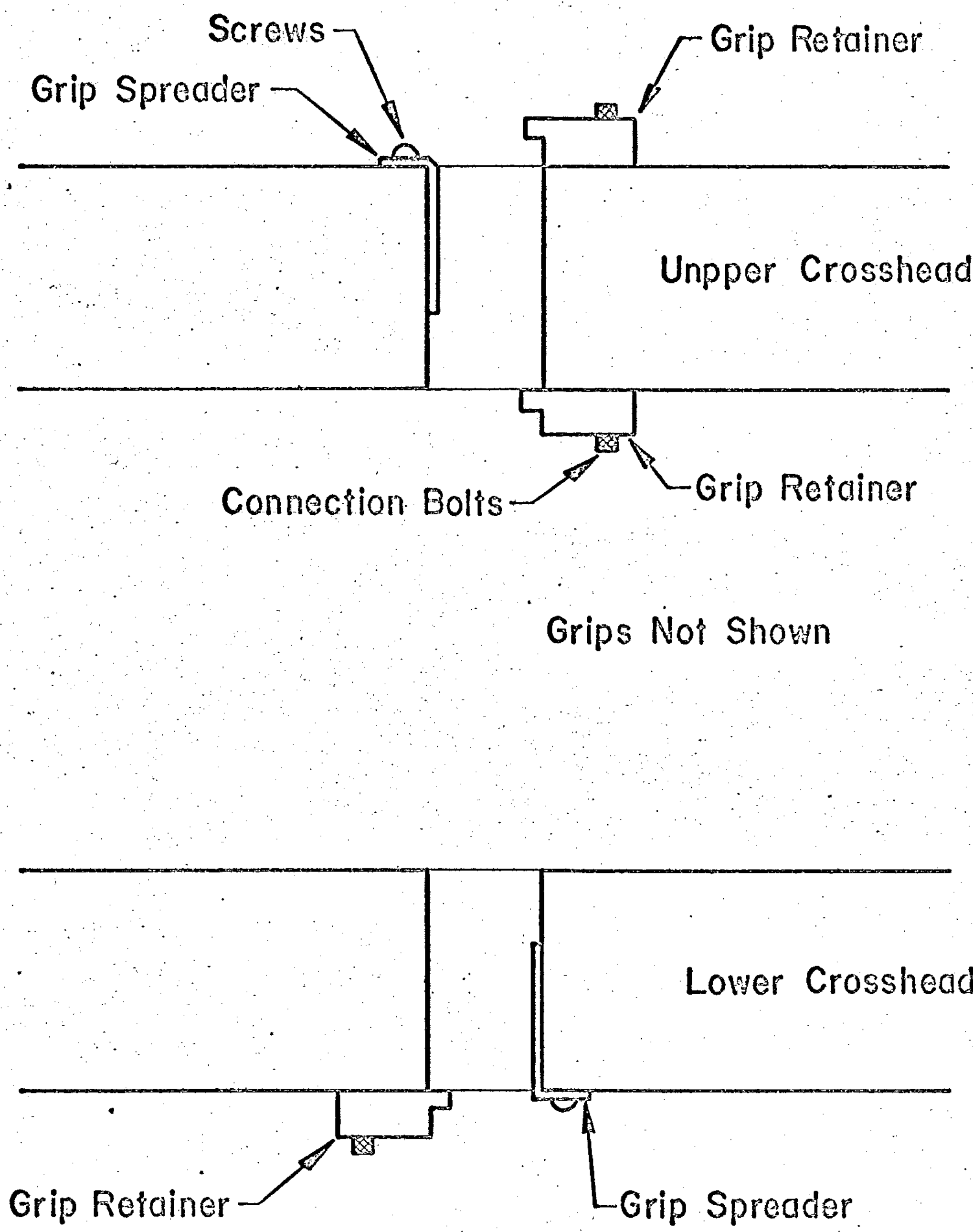


FIG. 20 FRONT VIEW OF SECTION THRU CROSSHEADS SHOWING THE ARRANGEMENT OF GRIP SPREADERS AND GRIP RETAINERS

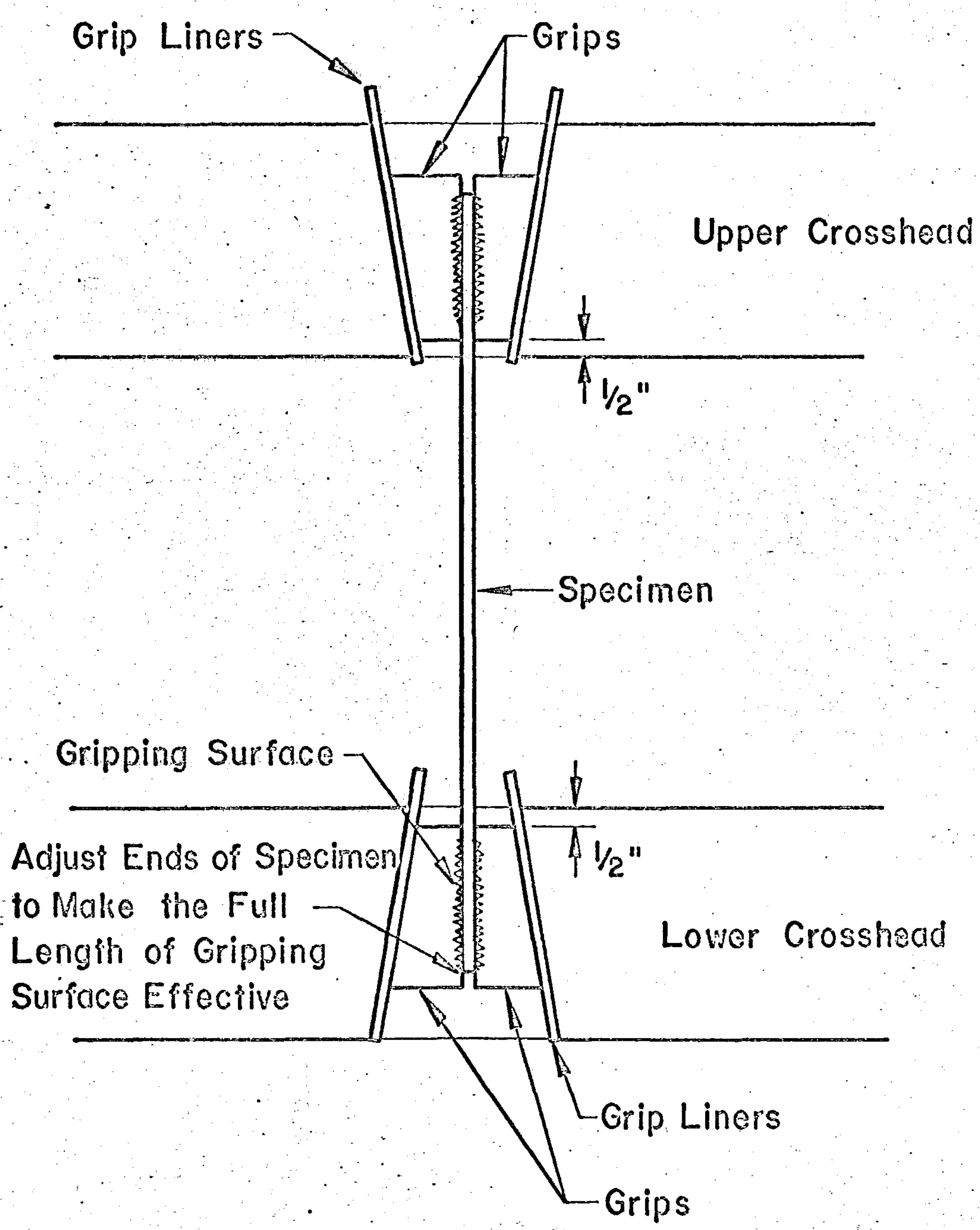


FIG. 21 SIDE VIEW OF SECTION THRU CROSSHEADS SHOWING THE CORRECT POSITION OF THE SPECIMEN AND THE GRIPS

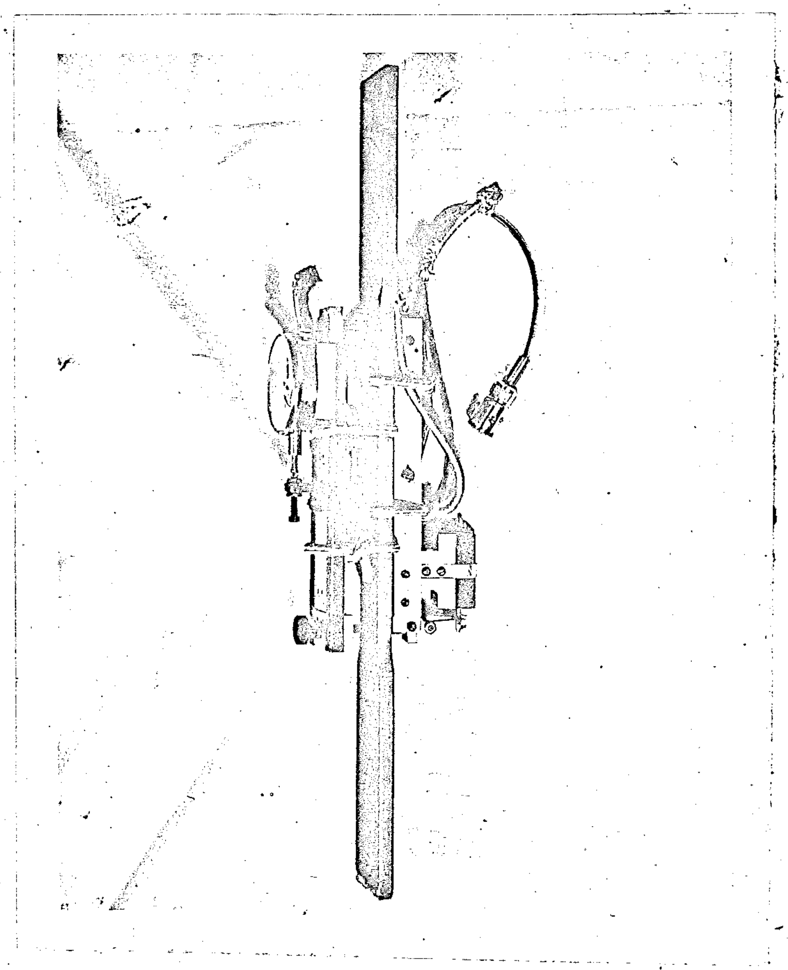


FIG. 22 A SPECIMEN WITH BOTH EXTENSOMETERS MOUNTED

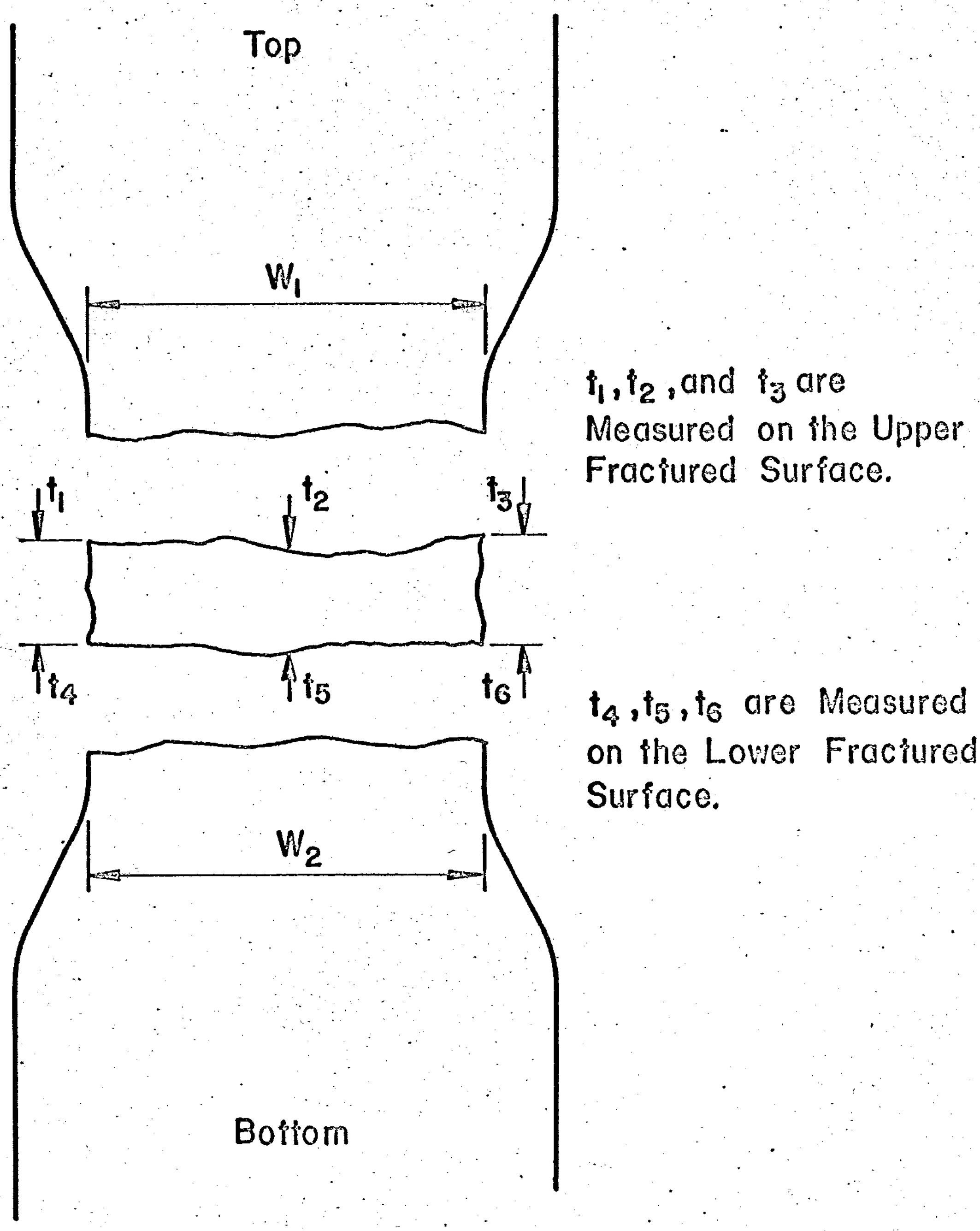


FIG. 23 MEASUREMENTS ON THE FRACTURED SPECIMEN

9. REFERENCES

1. AISC
   MANUAL OF STEEL CONSTRUCTION, American Institute of Steel Construction, New York, N. Y., Sixth Edition, Third Revised Printing, 1966.

2. ASTM
   1968 BOOK OF ASTM STANDARDS PART 4, American Society for Testing and Materials, Philadelphia, Pa. 1968.

3. Adams, P. F.
   PLASTIC DESIGN IN HIGH STRENGTH STEEL, Fritz Engineering Laboratory Report No. 297.19, May 1966.

4. Adams, P. F., Lay, M. G. and Galambos, T. V.
   EXPERIMENTS ON HIGH STRENGTH STEEL MEMBERS, Fritz Engineering Laboratory Report No. 297.8, July 1964.

5. Driscoll, G. C., Jr. et al
   PLASTIC DESIGN OF MULTI-STORY FRAMES, LECTURE NOTES, Fritz Engineering Laboratory Report No. 273.20, 1965.

6. Kim, S. W.
   EXPERIMENTS ON BEAMS: A572 GRADE 65, Fritz Engineering Laboratory Report No. 343.4 (In preparation).

7. Iyengar, S. N. S.
   STUB COLUMNS AND LOCAL BUCKLING, Fritz Engineering Laboratory Report No. 343.5 (In preparation)

8. Johnston, B. G., Editor
   COLUMN RESEARCH COUNCIL: GUIDE TO DESIGN CRITERIA FOR METAL COMPRESSION MEMBERS, John Wiley & Sons, Inc. New York, N. Y. 2nd Ed., 1966.

9. McClintock, F. A. & Argon, A. S. Editors
   MECHANICAL BEHAVIOR OF MATERIALS, Addison-Wesley Publishing Co., Inc., Reading, Mass., 1966.

10. ASTM
    1968 BOOK OF STANDARDS PART 31, American Society for Testing and Materials, Philadelphia, Pa., 1968.

11. Beedle, L. S. and Tall, L.
    BASIC COLUMN STRENGTH, Journal of the Structural Division, ASCE, Vol. 86, ST7, July 1960.

12. Rao, N. R., Lohrmann, M. & Tall, L.
EFFECT OF STRAIN RATE ON THE YIELD STRESS OF STRUCTURAL STEELS, Journal of Materials, Vol. 1, No. 1, March 1966, American Society for Testing and Materials, Philadelphia, Pa.

13. Johnston, B. and Opila, F.
COMPRESSION AND TENSION TESTS OF STRUCTURAL ALLOYS, Proceedings ASTM, Vol. 41, 1941 p. 552-570.

14. Haaijer, G.
BUCKLING OF UNIFORMLY COMPRESSED STEEL PLATES IN THE STRAIN-HARDENING RANGE, Fritz Engineering Laboratory Report No. 205E.7 August 1956.

15. Ramberg, W. and Osgood, R.
DESCRIPTION OF STRESS-STRAIN CURVES BY THREE PARAMETERS, NACA TN 902, 1943.

16. Lay, M. G.
THE STATIC LOAD-DEFORMATION BEHAVIOR OF PLANAR STEEL STRUCTURES, Fritz Engineering Laboratory Report No. 207.6, April 1964.

17. Desai, S. and Iyengar, S. N. S.
COMPUTER PROGRAM FOR ANALYSIS OF TENSION TEST DATA, Fritz Engineering Laboratory Report No. 343.8 (In preparation).

18. Tall, L.
MATERIAL PROPERTIES OF STEEL, Fritz Engineering Laboratory Report No. 220A.28, June 1957.

19. Iyengar, S. N. S.
COMPRESSION TESTS AND SIMULATED MILL TESTS ON A572 (Grade 65) STEEL SPECIMENS, Fritz Engineering Laboratory Report No. 343.6 (In preparation).

20. ASTM
ASTM MANUAL ON QUALITY CONTROL OF MATERIALS, STP15-C, American Society for Testing and Materials, Philadelphia, Pa. 1951.

V I T A

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